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Bioretention: Evaluating their Effectiveness for Improving Water Quality in New England Urban Environments

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BIORETENTION: EVALUATING THEIR EFFECTIVENESS FOR IMPROVING WATER QUALITY IN NEW ENGLAND URBAN ENVIRONMENTS

A Thesis Presented

by

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ABSTRACT

BIORETENTION: EVALUATING THEIR EFFECTIVENESS FOR IMPROVING WATER QUALITY IN NEW ENGLAND URBAN ENVIRONMENTS

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Nonpoint source (NPS) pollution has been identified by the USEPA (2005) as one of the leading causes of water quality problems in the United States. Bioretention has become one of the more frequently used stormwater management practices for addressing NPS pollution in urbanized watersheds in New England. Yet despite increased acceptance, bioretention is not widely practiced. This study explores and evaluates the efficacy of bioretention for protecting urban water quality.

This research found that numerous monitoring methods are used by researchers and industry experts to assess the effectiveness of stormwater best management practices (BMPs) and low impact development (LID) practices, including bioretention. The two most common methods for analyzing and evaluating water quality data are pollutant removal efficiency and effluent quality. While effluent quality data is useful for characterizing classes of BMP treatment performance on a statistical basis, pollutant removal efficiency is more representative of the actual pollutant load being reduced by the stormwater treatment practice over time, and is used in Total Maximum Daily Load (TMDL) assessments. However, despite this difference, monitoring is still arguably the best method for determining the effectiveness of stormwater treatment practices.

Monitoring of bioretention performance results is needed to inform improvements to design standards and guidance to aid state and local municipalities in the proper selection of bioretention/stormwater controls. This study advocates for instituting fine-scale, “safe-to-fail” design experiments as part of an adaptive management process that is used to advance bioretention design guidance and future applications of monitoring practice(s) that target reduction of pollutants in downstream receiving waterbodies. This innovative approach could result in increased use of bioretention in New England urban environments.

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CHAPTER 1

THE STATE OF WATER QUALITY

Introduction

Nonpoint source (NPS) pollution has been identified by the United States Environmental Protection Agency (USEPA, 2005) as one of the leading causes of water quality problems in the United States today. NPS pollution is defined as "rainfall or snowmelt moving over and through the ground, picking up, and carrying away pollutants that are deposited into rivers, lakes and coastal waters, or introducing them into the groundwater" (USEPA, 1996). Impervious surface cover is a major contributor to NPS pollution and is recognized as a reliable indicator of the degree of hydrological and water quality impacts of urban development (de la Crétaz and Barten, 2007; Chabaeva et al. 2009) because urban runoff flows contain various physical, chemical and biological pollutants from anthropogenic activities and natural processes. As a result, watershed hydrology and water quality are directly and significantly altered due to the increases in flood peaks, runoff volumes and pollutant loads, which, in turn, correspond to reductions in runoff lag times, groundwater infiltration and evapotranspiration (de la Crétaz and Barten, 2007; Li and Davis, 2009).

Traditional or conventional stormwater management controls used in many urban areas were once designed to collect, convey and discharge water as quickly and efficiently as possible to control flooding and dispose of wastewater (USEPA, 2000b). In particular, over 100 communities in New England are equipped with combined sewer drainage systems which carry sewage and stormwater from urban streets in the same pipe system (USEPA, 2004a; de la Crétaz and Barten, 2007). After heavy precipitation or snowmelt events, the wastewater and runoff volumes are often more than the sewer systems or wastewater treatment facilities can handle, and a combined sewer overflow (CSO) occurs. CSOs are a common occurrence in many cities across the United States (Figure 1-1) and these CSOs discharge directly into streams, rivers, lakes and coastal areas – representing a major pollution source. In addition, the natural hydrology of a receiving waterbody is adversely affected by the increase in volume and temperature of the excess runoff, as well as the increase of NPS pollution, which is now known to have severe environmental and human health impacts (USEPA, 2004b).

Figure 1-1: Combined Sewer Overflow Demographics in the United States (http://cfpub.epa.gov/npdes/cso/demo.cfm?program_id=5, 2004)

As a new, evolving concept, green infrastructure provides numerous ecological solutions to cities for mitigating the effects of climate change, managing stormwater to reduce urban runoff and pollutant loads, including CSOs, and protecting wildlife habitat and biodiversity (Benedict and McMahon, 2006). Green infrastructure can mean different things to different people and has been used to describe a variety of ideas and approaches to stormwater management. Benedict and McMahon (2006) define *Green Infrastructure* as “an interconnected network of natural areas and open spaces that conserves natural ecosystem values and functions, sustains clean air and water, and provides a wide array of benefits to people and wildlife”. In this definition, green infrastructure has a broad meaning based on ecological services designed to protect valuable networks of green spaces and natural areas, generally outside of built urban areas – often in peri-urban locations in metropolitan areas at the urban-rural interface. Green infrastructure has also been defined as a means of spatially organizing the built/urban environment to support key ecological processes and functions which integrate protected and constructed elements as the key to green infrastructure (Ahern, 2007). This definition pertains more explicitly to green infrastructure to provide multiple functions, and address environmental problems in urban environments.

More recently, green infrastructure has spurred the development of innovative stormwater management practices such as stormwater best management practices (BMPs) and low impact development (LID). Used in conjunction with traditional stormwater management methods, they are designed to minimize or disconnect impervious surface cover and maximize infiltration of wet weather precipitation to combat the effects of NPS pollution and manage urban runoff before reaching surface waters.

Yet despite these innovations, stormwater BMPs and LID practices are not widely used by New England city governments (Davis et al., 2009). This study will explore and evaluate the efficacy of one specific green infrastructure practice for improving water quality – bioretention – to determine if green infrastructure is the best or appropriate method of protecting waterbodies from the negative impacts of NPS pollution, including CSOs – in the geographical context of New England.

The Clean Water Act

The Clean Water Act (CWA) of 1972 marked a major shift in the management of United States water bodies, providing regulatory controls to address water quality problems. The Act was established to regulate pollutant discharge into rivers, streams, lakes, ponds and coastal areas, and to regulate quality standards for surface waters. Under Section 402 of the CWA, the United States Environmental Protection Agency (USEPA) created the National Pollutant Discharge Elimination System (NPDES) stormwater program which manages pollution control programs within each state. Under the NPDES regulatory program, each state must obtain a permit for *point* sources that discharge pollutants to surface waters. NPDES permits cover stormwater discharge from municipal separate storm sewer systems (MS4s), construction activities and industrial activities. These permits may not exceed five years and require jurisdictions to develop comprehensive stormwater management programs aimed at reducing point source pollution to the “maximum extent practicable” (USEPA, 2010a).

The NPDES is a comprehensive two-phased national stormwater program. Phase I of the NPDES stormwater program began in 1990 and applied to combined sewer overflows (CSOs) and MS4s in cities with a population greater than 100,000, new construction sites disturbing greater than five acres of land, and industrial activities in ten categories. Phase II expanded the NPDES permitting requirements to focus on urbanized areas with a population less than 100,000, construction sites of one to five acres, and the same industrial activities covered by Phase I. In addition, Phase II requires that a Notice of Intent (NOI) be submitted with a storm water pollution prevention plan (SWPPP) that addresses development and implementation of BMPs and measureable goals in six minimum control areas: public education and outreach; public participation and involvement; illicit discharge detection and elimination; construction site runoff control; post-construction runoff control; and pollution prevention/good housekeeping. Reports must be submitted annually during the first permit term and then biennially thereafter until the end of the five-year term.

States are individually authorized by the USEPA to administer their NPDES programs as long as they have demonstrated a robust permitting program is in place. In this case, each state is the permitting authority and performs all issuance and oversight activities. If a state does not have the authority to administer the NPDES program, then the USEPA is the permitting authority, like Massachusetts and New Hampshire within the New England region (Table 1-1).

Table 1-1: New England State NPDES Program Authority (Source: http://cfpub2.epa.gov/npdes/statestats.cfm)

State	Approved State NPDES Permit Program	Approved to Regulate Federal Facilities	Approved State Pretreatment Program	Approved General Permits Program
Connecticut	√	√	√	√
Maine	√	√	√	√
Massachusetts				
New Hampshire				
Rhode Island	√	√	√	√
Vermont	√		√	√

With the growing concern over stormwater runoff from agricultural land and urban areas, Congress passed Section 319 of the Clean Water Act in 1987, establishing a national program to control *nonpoint* sources of water pollution. Section 319 assists states in addressing NPS pollution through the development of assessment reports

(305(b) Report: National Water Quality Inventory Report to Congress); adoption of management programs to control NPS pollution; and implementation of those management programs. Unlike Section 402, the USEPA awards grants to states for the development and implementation of programs aimed at reducing pollution from nonpoint sources. A state receiving Section 319 funds must complete and update a NPS management plan every five years that includes identifying waters that are impaired or threatened by nonpoint sources of pollution (303(d) Report: Listing of Impaired Waters and Total Maximum Daily Loads Information), developing short- and long-term goals for cleaning them up, and identifying BMPs that will be used. Although the CWA provides no federal regulatory authority over the program, state NPS programs must also have a monitoring and evaluation plan, which is tied into the state 305(b) assessment and reporting program.

While the federally directed NPDES program has prompted considerable action by local governments to address point source pollution, efforts to reduce NPS pollution continue to grow. Since the USEPA has no regulatory authority over nonpoint sources, a federal grant program was created to provide funding to states for the development and implementation of their NPS management programs. Travis et al. (2004) explain that when the national government delegated responsibility for these programs to the states, the ability of the states to administer these programs and meet national environmental standards was brought to the forefront. In 1987, the Water Quality Act (WQA) was passed and created the Clean Water State Revolving Fund (CWSRF) which provides funding for states to create a program to address water quality goals within their state (Travis et al., 2004). However, research has indicated that the biggest challenge to program implementation continues to be lack of funding and personnel resources (Ice, 2004; White and Boswell, 2007). For example, over 50% of local governments in Kansas intend to rely heavily on the use of stormwater utilities as the primary funding mechanism for implementation of stormwater management plans and BMPs (White and Boswell, 2007). However, citizens who may oppose this taxing mechanism may resist the development of stormwater utilities. Therefore, without additional federal guidance on how to resolve these resource constraints, many communities will continue to struggle to implement successful programs.

In December 2009, a bill was introduced into Congress, the Green Infrastructure for Clean Water Act (H.R. 4202/S. 3561), making green infrastructure and low impact development techniques a national priority (ASLA, 2010). The act aims to allow states, localities and other qualified entities the ability to receive grants to plan, design and implement green infrastructure projects for addressing stormwater management, water quality and water quantity issues. In addition, this legislation would also establish 3-5 “Centers of Excellence for Green Infrastructure” across the country to provide technical assistance to state and local governments and conduct research on water resource enhancement (THOMAS, 2009-2010). The act would also establish a green infrastructure program within the USEPA’s Office of Water to promote the use of green infrastructure and integration of green infrastructure into permitting and other regulatory programs, codes and ordinance development. In 2010, the bill was referred to both House and Senate Committees where it was awaiting further action (ASLA, 2010). The bill had not passed before the advent of the 112^{th} U.S. Congress, and therefore, must be reintroduced in the new session: 2011 – 2013 (Civil Impulse, LLC, 2010).

On December 28, 2009, the USEPA issued a Federal Register (FR) Notice seeking stakeholder input to assist the USEPA in shaping a nationwide stormwater program to further reduce the impacts of stormwater runoff (FR, 2009). As described in the FR Notice, input on the following preliminary regulatory considerations were requested (FR, 2009):

- Expand the area subject to federal stormwater regulations
- Establish specific requirements to control stormwater discharges from new development and redevelopment
- Develop a single set of consistent stormwater requirements for all municipal separate storm sewer systems (MS4s)
- Require MS4s to address stormwater discharges in areas of existing development through retrofitting the sewer system or drainage area with improved stormwater control measures
- Explore specific stormwater provisions to protect sensitive areas

As part of this process, the USEPA is also soliciting input from the public on innovative stormwater controls to evaluate green infrastructure design techniques and approaches that mimic natural water processes (FR, 2009). In response to this call, the American Society of Landscape Architects (ALSA) is working with the USEPA to supply approximately 300 case studies on landscape architecture projects that successfully and sustainably manage stormwater runoff (ASLA, 2011). This is an important opportunity to show the USEPA how green infrastructure works, and how green infrastructure projects can be highly-effective and a cost-effective approach to improving water quality, while also providing additional ecosystem services.

Governance of State Stormwater Programs

United States local governments are facing extreme challenges in meeting water quality goals for our nation's surface waters. The United States Environmental Protection Agency (USEPA, 2009) reports that 44% of assessed rivers, 64% of assessed lakes and 30% of assessed bays and estuaries in the nation are polluted, citing agriculture, atmospheric deposition, unspecified sources and municipal discharges/sewage as the primary sources (Table 1-2). The 2004 National Water Quality Inventory Report indicates that more than 60% of all impaired waters are affected solely by nonpoint (NPS) pollution – pathogens (bacteria), organic matter, mercury, nutrients (phosphorus and nitrogen), metals and sediment (USEPA, 2009) – clearly illustrating the need for new solutions to address these negative effects on water quality.

Table 1-2: Summary of 2004 National Water Quality Inventory Report (USEPA, 2009)

Waterbody Type	Total Size	Amount Assessed (% of Total)	Amount Impaired (% of Total)	Sources *
Rivers (miles)	3,533,205	563,955 (16%)	246,002 (44%)	Agriculture, Hydromodification, Unspecified Sources
Lakes (acres)	41,666,049	16,230,384 (39%)	10,451,402 (64%)	Atmospheric Deposition, Unspecified Sources, Agriculture
Bays & Estuaries (sq. miles)	87,791	25,399 (29%)	7,641 (30%)	Atmospheric Deposition, Unspecified Sources, Municipal Discharges/ Sewage

* Represents the top three sources of impairment reported by states

Under current USEPA guidelines, the focus of watershed management is primarily aimed at solving severe water quality problems due to NPS pollution in a specific geographic location. Planning by state and local governments involves the development of Total Maximum Daily Loads (TMDLs) which sets an allowable pollution load that may be discharged into a receiving waterbody while still complying with water quality standards (USEPA, 2002). State water quality programs define their program goals by designating uses, such as drinking water, recreation, aquatic life and fish consumption, for all waterbodies, setting criteria to protect those uses and establishing provisions to protect waterbodies from pollutants in the future. In addition, these plans also identify alternative solutions and control measures for addressing NPS.

This thesis concentrates on reviewing stormwater treatment practices for two states within the New England region – the Commonwealth of Massachusetts and the State of Connecticut. Selection of these states was based on the following criteria: governance of stormwater controls, basis for and application of water quality controls, implementation of stormwater management practices, monitoring requirements and the connection to prior studies conducted in these states. In addition, the author has studied the past three academic years (2008-2011) in Massachusetts; and lives and will professionally work in the state of Connecticut.

Commonwealth of Massachusetts

For several years, cleanup efforts in the Commonwealth of Massachusetts have concentrated on industrial and municipal discharges from point sources which have resulted in some improvement in water quality. However, many of the waterbodies continue to be reported as impaired as evidenced in the 2006 National Water Quality Inventory Report (USEPA, 2010b) – 69% of assessed rivers, 88% of assessed lakes and 90% of assessed bays and estuaries (Table 1-3). This table also highlights that the amount of assessed waterbodies varies greatly, as well as the difficulty in determining the sources of impairment for all three waterbody types (e.g., "unspecified sources").

Table 1-3: Summary of 2006 National Water Quality Inventory Report for the Commonwealth of Massachusetts (USEPA, 2010b)

Waterbody Type	Total Size	Amount Assessed (% of Total)	Amount Impaired (% of Total)	Sources *
Rivers (miles)	8,229	2,372 (29%)	1,640 (69%)	Unspecified Source, Urban Runoff/Stormwater, Municipal Discharges/ Sewage
Lakes (acres)	151,173	94,212 (62%)	82,829 (88%)	Unspecified Source, Atmospheric Deposition, Land Application/Waste Sites/Tanks
Bays & Estuaries (sq. miles)	228	241 (106%)	218 (90%)	Unspecified Source, Urban Runoff/Stormwater, Municipal Discharges/ Sewage

* Represents the top three sources of impairment reported

State of Connecticut

To satisfy statutory reporting requirements of the Clean Water Act, the State of Connecticut submits reports to the U.S. Environmental Protection Agency every two years. The 305(b) report, National Water Quality Inventory Report to Congress, provides an assessment of the quality of its waters relative to attaining designated uses that are established by the State's water quality standards. The impaired waterbodies identified in this report are then given a priority ranking to develop Total Maximum Daily Loads (TMDLs) or other management action which is detailed in the 303(d) report, Listing of Impaired Waters and TMDL Information. Following a growing national effort to consolidate the two reports, Connecticut submitted its first fully integrated 305(b)/303(d) report for the 2006 reporting cycle under the opuses of the Connecticut Consolidated Assessment and Listing Methodology (CT CALM), and continues to follow this integrated approach today (CTDEP, 2008).

In the 2008 National Water Quality Inventory Report (USEPA, 2010b)**,** the State of Connecticut listed 42% of assessed rivers, 23% of assessed lakes and 69% of assessed bays and estuaries as impaired (Table 1-4). This table also highlights that only approximately 40% of rivers and lakes are assessed in Connecticut, as well as the difficulty in identifying some of the sources of impairment (e.g., "unspecified sources"). The geographic coverage of these assessed waterbodies is presented in Figure 1-2.

Table 1-4: Summary of 2008 National Water Quality Inventory Report for the State of Connecticut (USEPA, 2010b)

Waterbody Type	Total Size	Amount Assessed (% of Total)	Amount Impaired (% of Total)	Sources *
Rivers (miles)	5,830	2,099 (36%)	874 (42%)	Unspecified Sources, Urban Runoff/Stormwater, Municipal Discharges/ Sewage
Lakes (acres)	64,973	26,875 (41%)	6,220 (23%)	Legacy/Historical Pollutants, Unspecified Sources, Industrial
Bays & Estuaries (sq. miles)	613	611 (99%)	420 (69%)	Urban Runoff/Stormwater, Unspecified NPS Sources, Atmospheric Deposition

* Represents the top three sources of impairment reported

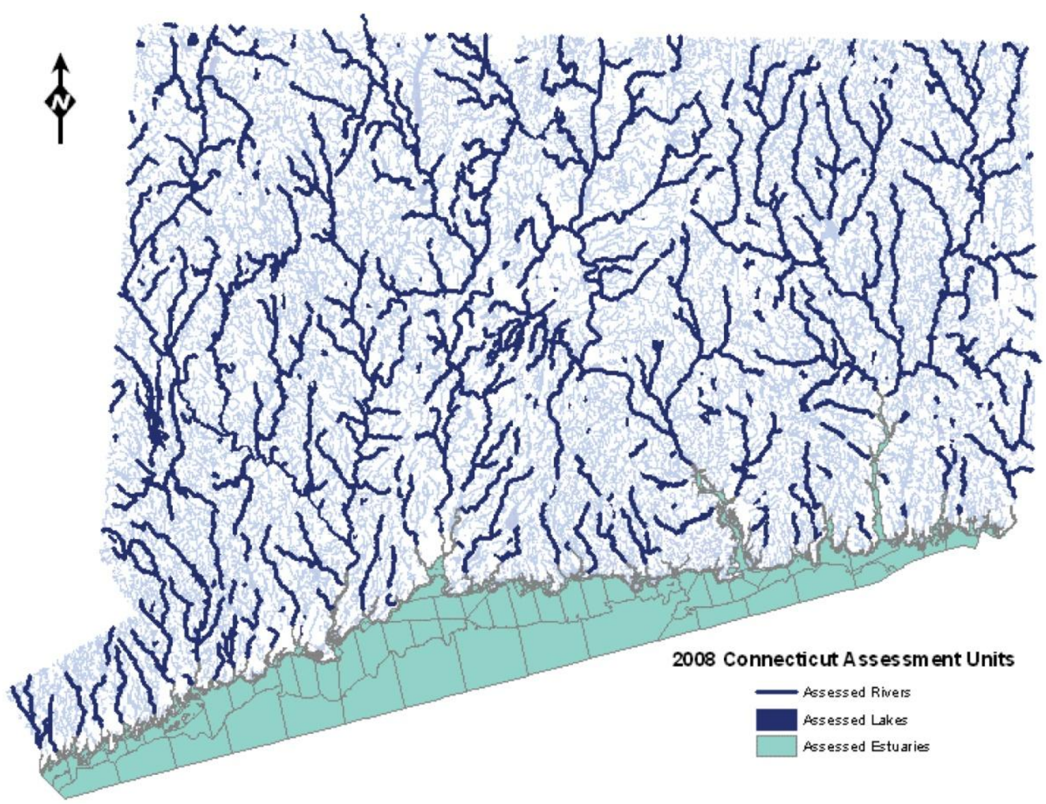


Figure 1-2: 2008 Connecticut Assessed Waterbodies (CTDEP, 2008)

The water quality data presented above emphasizes the extent at which our nation's waterbodies are degrading, but only at the level of what is assessed. Although the inventory reports for the Commonwealth of Massachusetts and the State of Connecticut account for only a fraction of the waterbodies monitored, water quality is a national concern that can arguably be best controlled with water quality standards and stormwater management programs implemented at the state level because keeping our surface waters clean and safe is critical to protect the drinking water supply, wildlife habitat and biodiversity, and to provide recreation for swimming and fishing. Monitoring helps federal agencies and local governments characterize their waterbodies and track trends of water quality over time, identify specific existing or emerging water quality problems, and gather enough information to design pollution prevention and remediation programs. Specific water quality standards and stormwater monitoring programs for the Commonwealth of Massachusetts and the State of Connecticut can be found in Appendix A and B, respectively.

Research Goals and Objectives

The primary goal of this thesis is to evaluate the effectiveness of bioretention specifically for its capability of infiltrating stormwater runoff and for water pollution mitigation. Determining stormwater management effectiveness should inform communities' decisions and choices of green infrastructure strategies for new development and retrofit development as an important approach to complement existing practices for managing stormwater runoff. This goal will be pursued through the following objectives:

1. Determine the monitoring methods and measurement criteria used by industry experts to assess performance of stormwater BMPs, LID and bioretention.

2. Determine if there are limitations in the performance of bioretention, from the perspective of retaining stormwater on site, infiltration rates and improvements to water quality.

3. Understand the effects of New England cold climates on bioretention performance, specifically temperature fluctuation, frost penetration and hydrology of snowmelt.

Through these objectives, the following questions will be addressed in the research:

1. How are stormwater BMPs, LID and bioretention practices selected for use in managing stormwater runoff and water quality improvement?

2. How is the effectiveness of stormwater BMPs, LID and bioretention determined?

3. What are the methods of monitoring performance of stormwater BMPs, LID and bioretention? What are the strengths and weaknesses of each method? How do these methods compare to each other? Are these methods accepted by industry experts?

4. Do differing climate conditions in New England affect performance of stormwater treatment practices like LID and bioretention?

5. Are bioretention strategies effective as agents of managing stormwater runoff and nonpoint source (NPS) pollution in New England urban environments?

6. How does bioretention performance monitoring affect industry design standards and guidance?

Summary and Chapter Outline

Watersheds in New England urban environments are not only affected by the amount of impervious surface cover, but also by the existing network of stormwater infrastructure and seasonal weather patterns. Conventional stormwater management practices are largely ineffective in mitigating the negative effects of NPS pollution. Therefore, additional data is needed on the performance and effectiveness of green infrastructure practices such as LID and bioretention for managing urban runoff.

This thesis is comprised of five chapters. This chapter presented a brief overview of the impact of NPS pollution, the role of traditional and innovative stormwater management methods, an overview of the national and state regulations/policies governing stormwater management practices, the stated goals and objectives of the study and the research questions that will be addressed. The literature review is covered in Chapter 2, and reviews the emergence of innovative stormwater management practices with a specific focus on bioretention, and an in-depth review of multiple modeling methods and techniques used to monitor stormwater BMPs, LID and bioretention, including the effects of cold weather conditions on stormwater infiltration and remediation.

Chapter 3 discusses the research design, analytical techniques and variables used for bioretention performance monitoring. Chapter 4 examines the various stormwater monitoring programs and protocols, followed by a discussion of the results of the monitoring methods reviewed, as well as the relationship to New England urban environments. Chapter 5 presents a conclusion, recommendations for design guidance and future applications of monitoring practice(s), contributions to the field of Landscape Architecture and identification of future research needs.

CHAPTER 2

LITERATURE REVIEW

Introduction

In recognition of current population growth forecasts and the demand for urban development (Figure 2-1), a better understanding of innovative stormwater management practices is arguably needed, as well as their integration into a framework for urban design and planning. Stormwater runoff from the built environment remains one of the greatest challenges of water pollution control today because NPS pollution is the prime contributor to water quality impairment of waterbodies nationwide (USEPA, 2005). Incorporating innovative stormwater management practices – stormwater best management practices (BMPs), low impact development (LID), and bioretention – can mitigate the negative effects of NPS pollution on New England waterbodies. Green infrastructure is a means of "spatially organizing urban environments" using ecological and physical processes to link the built environment with the natural environment (Ahern, 2007).

The aim of this literature review is to introduce the conceptual framework for using green infrastructure to address state and local municipalities' stormwater treatment practices for increasing water quality. A critical review of literature from multiple disciplines – Engineering, Hydrology, Planning, and Soil Science – will discuss the emergence and challenges of stormwater management practices, and the monitoring methods used to measure performance of those practices. Metrics for monitoring and analysis will be used to determine criteria for evaluating stormwater treatment effectiveness. Based on this review, recommendations for application of these monitoring methods to measure stormwater BMPs, LID and bioretention performance will be presented in this chapter and Chapter 5.

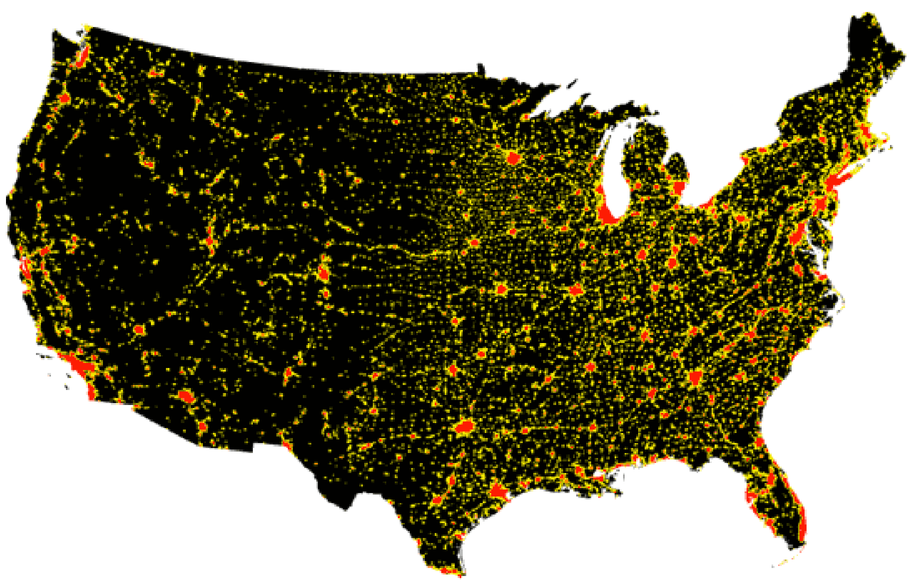


Figure 2-1: Urbanization Map of the United States Derived from City Lights Data. Urban areas are colored in red, while peri-urban areas are in yellow (image created by Flashback Imaging Corporation under contract with NOAA and NASA, http://science.nasa.gov/science-news/science-at-nasa/2000/ast15nov_1/, 2000)

Stormwater Management Practices

As nonpoint source (NPS) pollution continues to be the focus of watershed management within municipalities, development and implementation of effective stormwater best management practices (BMPs) have emerged as the key to controlling this inherently diffused and decentralized source (Ice, 2004). Stormwater BMPs are defined as “methods, measures or practices selected by an agency to meet its nonpoint source control needs” (40CFR130.2, 1976), and are designed to meet a variety of water quantity and water quality goals dependent on the needs of the watershed. In particular, implementation of stormwater BMPs and LID in urbanized areas undergoing development and redevelopment are recommended to focus on minimizing post-development peak discharge rates, volume of runoff and pollutant loads to mimic pre-development values. To this end, BMP efforts are directed towards addressing “flow control, pollutant removal and pollutant source reductions” (USEPA, 1999a) with the ultimate goal of protecting and/or improving the quality of receiving waters.

Under this broad categorization, stormwater BMPs in the United States are classified as structural or non-structural, and include controls, operation and maintenance procedures that can be applied before, during and after precipitation events and snowmelt to reduce or eliminate the introduction of pollutants into receiving waters (40CFR130.2, 1976). Structural BMPs (Table 2-1) are defined as "engineered and constructed systems that are used to treat stormwater at either the point of generation or the point of discharge to either the storm sewer system or to receiving waters" (USEPA, 1999a; 2002). Non-structural BMPs (Table 2-2) can be described as "institutional, educational and pollution-prevention practices designed to prevent or minimize stormwater pollution and/or reduce the volume of stormwater requiring management" (USEPA, 1999a; 2002).

Table 2-1: Types of Structural and Non-structural Stormwater BMPs (Urbonas, 1994; USEPA, 1999a; 2002)

Structural BMP	Non-structural BMP
Detention Basins/Ponds	Automotive & Hazardous Material Disposal
Retention Ponds	Modified Use of Fertilizers, Pesticides
Constructed Wetlands	Animal Waste Disposal
Biofiltration/Bioretention Systems	Education & Outreach Programs
Grassed Swales & Filter Strips	Good Housekeeping (Commercial, Retail, Industrial)
Proprietary Manufactured Systems (hydrodynamic devices)	Maintenance Practices – street sweeping, catch basin cleaning
Pervious Pavement	Low Impact Development (includes pervious pavements and bioretention)

The BMP selection process is a complex one, especially when considering site-specific requirements, costs, local regulations/requirements, etc., but a critical and necessary step in establishing a comprehensive stormwater management program for effectively managing urban runoff. In its guidance on controlling NPS pollution from urban areas (USEPA, 2005), the USEPA recommends first establishing a legal framework in which to build the foundation for establishing a stormwater management program, which is also recommended by the Center for Watershed Protection (2008). Many state-level programs, like Massachusetts and Connecticut, must derive their legal authority from laws, codes and regulations within their respective states. In the absence of such legislation, states are forced to look outside their jurisdiction for statewide runoff management guidance (USEPA, 2005). In a Wisconsin case study, inconsistency in the governance structure proved to be an obstacle in the implementation of bioretention systems in a St. Francis, WI subdivision (Morzaria-Luna et al., 2004). Bioretention systems supplemented traditional stormwater practices, instead of replacing them, because developers were unsure of how to meet the dual stormwater standards (Morzaria-Luna et al., 2004).

Because of the very nature of controlling stormwater runoff, selection of the appropriate stormwater BMP or LID practice should be carefully tailored for a specific location to ensure that any constraints are addressed. For this reason, state and local governments evaluating stormwater treatment practices must consider reliable information that is pertinent to their locale, otherwise deploying applications inappropriately can lead to inconsistent implementation and failed treatment practices (Taylor and Fletcher, 2007). BMP performance studies in similar regions, climate and site conditions, as well as recognized industry-developed design guidance should serve as the basis for stormwater treatment decisions. Sources such as the International Stormwater BMP Database (ASCE, USEPA, WERF, FHWA, and APWA, 2004) and the National Pollutant Performance Database (CWP, 2007) provide useful information on stormwater BMP and LID performance. BMP costs and public acceptance of these practices should also be considered in the process of selecting stormwater BMPs and LID practices, such as bioretention.

Although comparing and selecting stormwater BMPs and LID practices can be a difficult undertaking, these practices represent a very large and diverse set of tools relative to performance, cost and maintenance needs. However, widespread usage of these practices has been hindered by the stormwater industry not having a broad and solid knowledge base in relation to the performance of non-structural measures (Taylor and Fletcher, 2007) considering that non-structural measures are a fairly new stormwater treatment practice that also requires additional data on performance of their hydrological and pollutant removal capabilities (USEPA, 1999a; 2002; Taylor and Fletcher, 2007). Evaluating this information to develop a better understanding of the types of issues that must be addressed when selecting stormwater BMPs and LID practices, state and local governments can effectively remove some of the uncertainty from the process and help ensure that their efforts to improve water quality succeed. Analysis of historical rainfall distributions and intensities for specific site locales/regions can be used to determine the effectiveness of non-structural BMPs for stormwater control – based on the following typical conditions (PGC, 2007; UNHSC 2010):

1. Drainage area: 0.5-1 acre
2. Land Cover: 90-100% impervious, where most precipitation translates to runoff
3. Ponding Depth: 0.5-12” above the surface bed
4. Soil Depth: 18-24”
5. Surface Area: 5% of the contributing drainage area
6. Infiltration Rate: 1” per hour

Adjusting variables such as the surface area and/or the projected infiltration rate will likely affect the amount of runoff infiltrated and treated by the non-structural control measure (PGC, 2007). Employing non-structural stormwater BMPs without fully understanding their effectiveness, cost of implementation and actual benefits (Urbonas, 1994; Taylor and Fletcher, 2007) suggests that establishing monitoring and evaluation protocols should improve and increase usage.

Low Impact Development

Low Impact Development (LID) is a concept that was pioneered by Prince George's County, Maryland Department of Environmental Resources in the early 1990s as an innovative approach to urban stormwater management. The primary goal of LID is to maintain or replicate a site's predevelopment hydrology using design techniques that infiltrate, filter, store, evaporate, and detain runoff close to its source (Prince George's County, 1999; USEPA, 2000b; Dietz, 2007). LID practices are implemented at the site level to manage runoff volumes and their impacts, as well as to reduce or eliminate the need for conventional structural BMPs. These multifunctional site designs include minimizing impervious areas, directed growth through master planning and zoning ordinances, protecting sensitive areas, preserving open/green space and minimizing soil and vegetation disturbance (Prince George's County, 1999; USEPA, 1999a; 2000b). In addition, the use of LID practices is less costly to implement and generally more aesthetically pleasing than traditional conveyance systems, and integrates well into the existing infrastructure (USEPA, 2000b).

LID provides opportunities to implement pollution controls and address environmental issues in retrofitting existing highly urbanized areas and in new developments (Figure 2-2). Measures, such as green roofs, permeable pavements, grass/vegetated swales or bioswales, rain barrels, and bioretention and rain gardens, provide a means to address both runoff volume reduction and pollutant removal. However, the appropriate use of LID practices requires careful consideration of site conditions (soil permeability, slope of terrain, water table depth, etc.), and may necessitate implementation of structural BMPs in conjunction with LID measures in order to achieve watershed objectives (Prince George's County, 1999; USEPA, 2000b; Dietz, 2007). In addition, LID technologies are still somewhat immature, requiring the need for more data on design and performance metrics (Table 2-2) relative to the hydrological impacts and pollutant removal data to substantiate LID as a sustainable practice (Davis et al., 2009). The application of LID practices may not be suitable for all sites. For example, in areas where high pollutant loading exists, such as recycling centers or gas stations, or brownfields with high soil contamination, LID practices may not be appropriate because of the risk of contaminating the groundwater (Dietz, 2007). In addition, steep slope conditions and seasonally high water tables may also be places where LID practices are not appropriate (Dietz, 2007).

Figure 2-2: Comparison of a Traditional and LID Development (PSAT, 2005)

Table 2-2: Metrics and Impacts of LID Technologies Needing Further Research (Davis et al., 2009)

Description	Design/Performance or Measurement Criteria
LID Design Information	Soil/Filter media composition, depth and configuration
	Drainage configuration
	Ponding depths
	Vegetation
	Maintenance
	Sizing of LID and BMPs in the context of urban watersheds and subwatersheds
LID Performance Information	Pollutant removal (total nitrogen, total phosphorus, total suspended solids, heavy metals)
	Pollutant removal efficiencies (USEPA, 1999a; Davis et al., 2009)
	Pollutant load reduction
	Influent and effluent concentrations
Hydrology Impacts	Peak discharge control
	Time of concentration
	Groundwater infiltration
	Evapotranspiration

Low Impact Development (LID) is an innovative approach to land development or redevelopment that works with nature to manage stormwater close to the source of where it's generated. LID employs a set of principles that preserves and recreates natural landscape features, while minimizing effective impervious surfaces to create functional and appealing site drainage that treats stormwater as a resource. Through implementation of LID, stormwater can be managed in a way that reduces the impact of the built environment while promoting the natural movement of water through the ecosystem or watershed. When applied on a wide scale, LID has been found to maintain or restore a watershed's hydrologic and ecological functions through increased retention of stormwater and pollutants on site and replicating predevelopment site conditions (USEPA, 2000b; Dietz 2007).

Bioretention

Over the last fifteen years, bioretention, or rain gardens, has become one of the most frequently used stormwater BMPs in the United States (Davis et al., 2009). The concept of bioretention originated in the early 1990s by Prince George's County, MD, Department of Environmental Resources as a stormwater practice that uses shallow storage, landscaping and soils (Figure 2-3) to control the quality and quantity of water by collecting it before it's filtered through plantings and soil media (Prince George's County, 1999; 2007; USEPA, 1999b; 2002; Dunnett and Clayton, 2007).

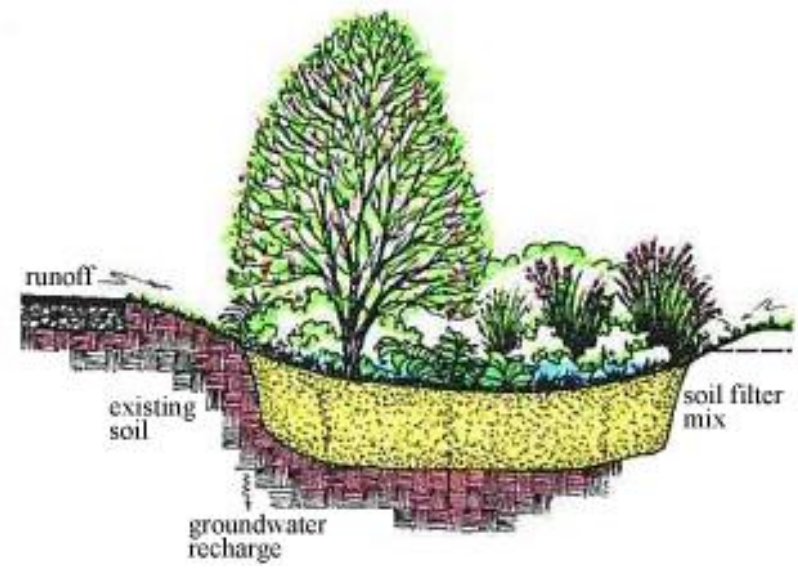


Figure 2-3: Typical Cross Section of a Bioretention Design (Prince George's County, 2007)

Bioretention systems are designed to function in much the same manner as physical, chemical and biological processes function in the natural environment – infiltration, filtration, storage, adsorption and evapotranspiration to name a few. As a result, these processes aid in replicating pre-existing hydrologic conditions by treating the runoff volume and by removing pollutants from the stormwater runoff. Another element of bioretention is in controlling runoff close to the source of where it is generated. Employing bioretention in urban environments for management of stormwater runoff provides opportunities for achieving several objectives, including: (1) maintaining and increasing groundwater recharge and base flow; (2) surface and groundwater pollutant removal; (3) stream channel protection; and, (4) peak flow reduction (Davis et al., 2007; Dietz, 2007).

In addition to the hydrologic benefits outlined above, bioretention is also capable of reducing thermal pollution which is important for cold water fisheries and stream habitats (PGC, 2007). Bioretention demonstrates a multitude of additional benefits, most important of which is the protection of ecosystem integrity, which includes conserving resources, creating wildlife and native plant habitats, nutrient cycling, soil chemistry, improving air quality, reducing energy use and mitigating urban climates (PGC, 2007; Jones and Jha, 2009). In addition, the value of individual and neighborhood properties with and/or adjacent to bioretention systems have been shown to increase by 20% due to the aesthetically pleasing landscape (PGC, 2007). On the other hand, public health concerns have been raised relative to bioretention being breeding grounds for mosquitoes (USEPA, 2005); however, mosquitoes need four days of standing water to develop as larva (PGC, 2007). To reduce this risk, ponding depths and infiltration rates of bioretention systems must be linked together to reduce extended periods of standing water (PGC, 2007; Davis et al., 2009). For instance, the Prince George's County Bioretention Manual (2007) recommends an infiltration rate of 1"/hour or greater (not to exceed 4 hours) for an infiltration bioretention system with a soil media depth of 2.5 feet, to account for ponding depths of 6- 9"/hour above the filter bed (Davis et al., 2009). Removing pathogenic bacteria is another major water quality concern, especially in coastal areas (Davis et al., 2009). Theoretically, bioretention should remove most forms of bacteria because of its design intent to capture and filter water, and subsequent dry out which exposes the bacteria to dry conditions and sunlight (Davis et al., 2009), but very little literature is published on this subject.

The performance of bioretention systems is generally affected by soil types, site conditions and surrounding land uses. Each design component of bioretention contributes to the functioning of the system, aiding in the removal of pollutants and reduction of stormwater runoff. To illustrate this point, six components typically found in bioretention systems are described below (USEPA, 2000b; 2005; Davis et al., 2009; CWP, 2010):

- Pretreatment – use is dependent on site, available surface area and type of treatment. Grass buffer strips or swales have been used to reduce runoff velocity and filter particulate matter before the runoff reaches the bioretention cell. Where space is a limiting factor, a surface mulch layer can be added to the bioretention system to act as the pretreatment mechanism in lieu of filters strips/swales.

- Ponding Area – provides storage of excess runoff before it filters through the soil bed, and facilitates the settling of particulates and evaporation of excess water. Ponding depths consider such elements as available surface storage ponding volume, subsoil infiltration rates, void storage space in soils/filter media, and maintenance practices.

- Organic Mulch Layer on the surface of the soil – performs the following functions: (1) acts as a filter for pollutants in the runoff, (2) retains moisture in the plant root zone, (3) decomposes leaves and organic material, (4) provides a medium for biological growth (microorganisms) to degrade petroleum-based pollutants, and (5) protects the soil from drying and prevents soil erosion of the soil bed.

- Soil Media – provides water and nutrients to support plant life in the bioretention system, and provides the area for stormwater storage and nutrient uptake by plants. The infiltration rate provides for periodic saturation which allows soils to be well-drained to maintain aerobic conditions. The composition of planting soils recommended by Prince George's County (2007) consist of 50% sand, 30% topsoil and 20% organic material to assist in the adsorption of pollutants – hydrocarbons, heavy metals and nutrients (total suspended solids, phosphorus and nitrogen).

- Sand Bed – provides aeration and drainage of the root zone in the planting soil and assists in the infiltration capacity of the bioretention system and flushing of pollutants from soil materials. In addition, the sand bed underlies the planting soil which allows water to ultimately drain into the surrounding soil.

- Vegetation – functions in the removal of water through evapotranspiration and pollutant removal through nutrient cycling, and is representative of a terrestrial forest ecosystem that uses native plant species. The root zone promotes soil permeability while the surface vegetation diverts and slows surface flow while filtering sediments. Pollutant removal is dependent on the area of plant community created, age of the plants and continued maintenance (Coffman et al., 1994).

According to the Prince George's County Bioretention Manual (2007), bioretention design models initially focused on designs of upland, terrestrial, forested systems because of the efficiency in replicating predevelopment hydrologic conditions. More recently, new designs have been explored and added to the manual – meadow habitat and garden themes – due to the multifunctional use of bioretention to complement existing site constraints and landscape elements (PGC, 2007). Bioretention designs can be installed in commercial and industrial applications, as well as in residential settings, combining landscape elements with stormwater management controls to intercept runoff from impervious surfaces. Once the runoff is captured by the bioretention system, water may pool at the surface of the soil media before infiltrating into the subsurface or by means of an underdrain, or a combination of the two. Depending on the severity of the storm event or snowmelt, overflow conditions and flow paths must be evaluated to ensure stable outlets are provided (Davis et al., 2007).

Bioretention can be implemented in a number of additional applications such as: roadway projects, institutional developments, redevelopment communities, revitalization and smart growth projects, urban retrofit stormwater management projects, streetscape projects, and parks and trailways (PGC, 2007). In addition to the various applications, numerous types of bioretention systems can be designed according to individual sites and site-specific constraints. Typical bioretention areas include parking areas with or without curbs, traffic islands, and swales that receive runoff from impervious surfaces: rooftops, parking lots and streets. Figure 2-4 and 2-5 illustrate two examples of bioretention applications.

Figure 2-4: Bioretention System Intercepting Runoff from an Adjacent Parking Lot at University of Massachusetts (Photo: Mary Dehais)

Figure 2-5: Bioretention System Intercepting Runoff from a High Density Traffic Roadway in Bridgeport, CT (Photo: Tom Tavella)

Bioretention is flexible in design which affords many opportunities for the Landscape Architect/Designer to be creative. The Prince George's County Bioretention Manual (2007), Low Impact Development Technical Guidance Manual for Puget Sound (PSAT, 2005), New York State Stormwater Management Design Manual (CWP, 2010) and San Francisco Stormwater Design Guidelines (SFPUC, 2010) offer the following guidance in determining when to use bioretention for stormwater control:

1. Placement is close to the source of runoff generation.

2. The site permits the dispersion of flows and bioretention systems can be distributed uniformly.

3. Sub-drainage areas are limited to less than 1-2 acres, and preferably less than 1 acre.

4. Available room for installation, including setback requirements. Setback considerations include building foundations, basements, property lines, drinking water wells, and public right-of-ways.

5. The stormwater management site integration is a feasible alternative to end-of-pipe BMP design.

6. Suitable soils are available at the site.

7. Slopes are 5% or less. To slow down the flow of the runoff, check dams or other flow control devices can be incorporated for slopes greater than 5%.

8. Depth-to-water table is at a minimum separation of 1' from the seasonal high water mark to the bottom of the bioretention cell where the contributing area has less than 5,000 sq.ft. of pollution-generating impervious surface; less than 10,000 sq.ft. of impervious surface; or less than .75-acres of lawn. Where the contributing area equals or exceeds these thresholds, a minimum separation of 3' from the seasonal high water mark to the bottom of the bioretention cell is recommended.

The goal of bioretention and LID practices is to replicate pre-development hydrology in post-development conditions; therefore, sizing a bioretention system is an important component of bioretention design. Several factors must be considered when determining the intended purpose of bioretention design (PGC, 2007), including (1) site requirements for water quality and quantity control; (2) design storm requirements needed to meet stormwater management criteria; (3) site constraints affecting the use of bioretention for water quality and quantity control; and, (4) installation of bioretention as an independent system or in parallel with existing infrastructure. Determining the design storm, design depth and storage volume are dependent on the infiltration characteristics of the media in the bioretention system, as well as flood protection and pollutant removal objectives (Davis et al., 2009).

Research by Davis et al. (2007) validates much of this guidance, but also notes that definition and drainage area relative to the minimum and maximum requirements have recently become topics of debate with regard to larger watersheds and high water table limitations. In a study comparing the hydrologic benefits of six bioretention systems in Maryland and North Carolina, design variation allowed "some" investigation of design and performance correlation, but Li et al. (2009) considers this aspect a current drawback of widespread implementation of bioretention across jurisdictions. With more than ten years of experience since the first application by Prince George's County, existing sizing procedures and criteria may need to be reevaluated and updated.

Maintenance and inspection of bioretention cells are critical to sustaining performance of the system. Although much of the maintenance is aesthetic in nature, e.g., removing trash, pruning, and adding mulch, hydrologic performance-based maintenance activities must also become part of the routine maintenance regime. Removing debris from the outflow inlet ensures that flow characteristics are not compromised from clogging. Plants provide enhanced environmental benefit over time – root systems and leaf canopies increase, and pollutant uptake and removal efficiencies. Soils, however, begin filtering pollutants immediately and can lose their ability to function in this capacity over time (USEPA, 2000b). Annual soil fertility tests are recommended (USEPA, 2000b), and replenishing the mulch layer annually and occasionally removing and replacing the top 1-2" of soil media with sand or other soil media has been shown to maintain required bioretention infiltration rates (PGC, 2007; Davis et al., 2009). Studies conducted by Li and Davis (2008) indicate that sediment and heavy metals accumulate in the top 0.4"-0.8" of soil media, therefore, removing and replacing surface layers with mulch and soil media may revitalize water quality performance. Caution should be exercised, however, because maintenance is heavily dependent on the catchment use and stability, and the presence of pretreatment (Davis et al., 2009).

Bioretention, or rain gardens, is a viable option when implemented in the environment to provide stormwater controls. As a stormwater management system, it is one of the most popular methods deployed by state and local municipalities, because of its versatility, flexibility in design, and application to various sites. In addition, bioretention provides multi-functional benefits, such as hydrological, ecological, aesthetics, and public health that complement volume reduction and pollutant removal capabilities – all while using natural landscape elements and soil media to do so. Although bioretention has mostly been implemented in small scale watersheds, current bioretention design guidance should be updated to address larger scale watershed applications, as well as bioretention design variations with respect to different soil media and soil depths that target phosphorus, nitrogen and bacteria removal. Implementing annual maintenance practices into stormwater management programs, such as removing debris from inlets and outlets to avoid clogging, adding mulch to bare areas, replacing dead plants and trimming vegetation, is a key aspect of sustaining performance of bioretention systems and should not be overlooked as a required element.

Rain Gardens

Rain gardens were developed by Prince George's County, MD as a concept of small bioretention systems for use in single/multi-lot residential areas (USEPA, 1999a). The term is now used synonymously with the concept of bioretention. The USEPA classifies rain gardens as filtration BMPs, as opposed to infiltration or storage BMPs, in that the water is stored above the surface and the infiltration rate is controlled by vegetative practices and the soil below (USEPA, 2000b).

Rain gardens are vegetated surface depressions located at low points in landscapes to capture stormwater runoff received directly from roofs, parking lots and roads (Dussaillant et al., 2005). In suburban settings, rain gardens also have been described as “shallow planted depressions” designed to manage excess rainwater runoff from homes/buildings and their associated landscape (Dunnett and Clayton, 2007). They provide numerous environmental functions that include: infiltrating stormwater runoff close to its source; reducing stormwater runoff by decreasing impervious surfaces; and, using native plants and soils to filter pollutants carried by stormwater runoff (USEPA, 2010a). In short, rain gardens facilitate groundwater recharge that improves water quality and preserves the water supply for humans and wildlife (Asleson et al., 2009).

Rain gardens are often confused with bioswales because of their similar landscape characteristics and functionality. Bioswales, or landscape swales, are vegetated or grassed open, linear channels that are designed to “attenuate and treat stormwater runoff for a defined water volume” (USEPA, 2006a). They generally transport larger stormwater volumes from a source to a discharge point, which promotes slowing, cleansing and infiltration of the stormwater along the way. A sloped base to facilitate this water movement distinguishes bioswales from rain gardens. Check dams are sometimes installed on sloped terrain to reduce the influence of the slope and prevent erosion caused by excess flow (Dunnett and Clayden, 2007). Most bioswale applications can be seen along roadsides and parking lots, but unlike a bioswale that is intended to direct water elsewhere, a rain garden is a final destination point (Figure 2-6 and 2-7).

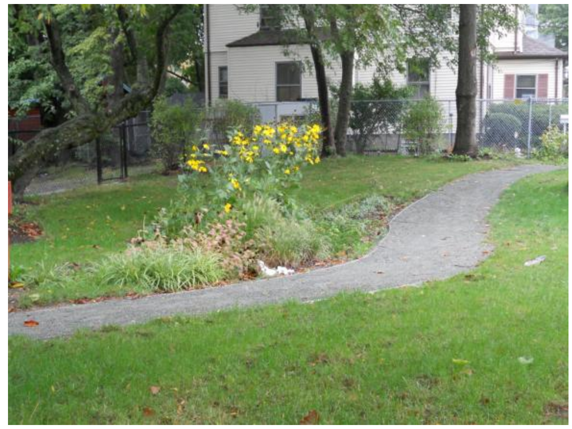


Figure 2-6: (Left) Grassed Bioswale between Two Parking Lots at Different Elevations at Hampshire College (Photo: Mary Dehais)
Figure 2-7: (Right) Rain Garden Intercepting Runoff from a Walkway and Adjacent Landscape in Dorchester, MA (Photo: Mary Dehais)

Bioretention systems offer a unique opportunity to Landscape Architects and Designers, as well as state and local municipalities, to not only manage stormwater, but also to rethink how designs and management of open space and the built environment can improve their environmental and aesthetic quality. It is for this reason that bioretention was chosen as the subject of this study.

Performance Monitoring and Assessment

Historically, monitoring efforts of many states and local municipalities have focused primarily on managing peak stormwater discharges from traditional, conveyance-type stormwater controls to protect against flooding, and not specifically on water quality controls (USEPA, 2002). From 1978 to 1983, the Nationwide Urban Runoff Program (NURP) was the one of the first comprehensive monitoring programs to evaluate the significance of priority pollutants in urban stormwater runoff. These evaluations indicated that urban runoff was contributing significant levels of pollutants into our nation's waterbodies and that stormwater control measures were warranted (USEPA, 1999a). In addition, the investigations also revealed that there was insufficient data available to quantify the degree of impacts attributable to urban runoff and to evaluate the effectiveness of the various stormwater control practices (USEPA, 1999a).

Over the past thirty years, many state and local governments have been monitoring urban stormwater BMPs, LID and bioretention to reduce the negative impacts of point and nonpoint source pollution on U.S. surface waters. The International Stormwater BMP Database project was launched in 1996 as a cooperative agreement between the USEPA and the American Society of Civil Engineers (ASCE) Urban Water Resources Research Council (UWRRC) in response to growing efforts by both public and private entities to comply with the Clean Water Act (GC&WWE, 2009). The primary goals of the database were to develop a standardized set of monitoring and reporting protocols for urban stormwater BMP performance studies, and to assemble and summarize data from historical and ongoing BMP investigations into a standardized format to facilitate performance analysis. As part of this project, a monitoring manual was developed to promote collection of more useful and representative data associated with BMP studies, and more consistent reporting of monitoring results for inclusion in the BMP database. In its second release, guidance for monitoring Low Impact Development (LID) has been incorporated.

Stormwater Monitoring Parameters

To evaluate the effectiveness of stormwater BMP or LID practices, monitoring parameters of a stormwater monitoring plan need to be defined in order to meet established program objectives. Basic parameters consist of hydrologic and hydraulic monitoring, and water quality monitoring. Collecting water quantity data is an important monitoring parameter because water balance equations are based on accurate flow measurements for determining total volume captured and reduced. Precipitation and other meteorological data are also key components of watershed water balances and needed to evaluate LID practices (GC&WWE, 2009). Hydrologic and hydraulic parameters are outlined in Table 2-3. Because stormwater runoff contains a variety of pollutants that can adversely affect receiving waterbodies, water quality data is collected and used in conjunction with water quantity data to form a complete assessment. Typical urban stormwater runoff constituents are listed in Table 2-3. The choice of which constituents to test is dependent on specific site conditions and the objectives of the monitoring program.

Table 2-3: Typical Urban Stormwater Runoff Constituents (GC&WWE, 2009)

Monitoring Parameters	
Hydrologic & Hydraulic	**Water Quality**
Precipitation	Conventional
Other Meteorological Data	pH
Temperature	Conductivity
Humidity	Temperature
Wind Speed	Turbidty
Barometric Pressure	Total Suspended Solids
Evapotranspiration	Suspended Sediment Concentration
Flow Measurements	Total Hardness
	Chloride
	Nutrients
	Orthophosphate
	Total Phosphorus
	Total Kjeldahl Nitrogen
	Nitrate + Nitrite
	Ammonia Nitrogen
	Metals
	Cadmium
	Copper
	Lead
	Zinc
	Bacteria
	Fecal Coliform
	E.coli
	Enterococci
	Other
	Total Petroleum Hydrocarbons

Since the Nationwide Urban Runoff Program (NURP), the International Stormwater BMP database and programs alike, many studies have been conducted to evaluate the performance of stormwater best management practices (BMPs), LID and bioretention by monitoring water quantity and water quality. However, in order to reach appropriate conclusions about volume reduction and water quality benefits, long-term, continuous studies are recommended to monitor longer periods of time to ensure a sufficient number and variety of storms and weather conditions are observed (USEPA, 1999a; 2002; Asleson et al., 2009; GC&WWE, 2009). Much of this concern originates from a lack of accurate and consistent water quality data that is collected, analyzed and reported on the performance of LID and bioretention systems, specifically for: (1) determining the effectiveness of stormwater management practices; (2) assessing performance when numerous monitoring methods, sampling techniques and data reporting requirements are used; and, (3) quantifying, measuring and comparing pollutant loads and pollutant removal efficiencies (USEPA, 1999a).

Water Quality Monitoring

The most commonly used method of evaluating stormwater BMPs and individual LID practices like bioretention is based on collecting composite samples and comparing pollutant concentration levels at specified inflow and outflow points (USEPA, 1999a; GC&WWE, 2009). Approaches for obtaining composite samples consist of *time-weighted*, collecting individual samples of equal volume at equal time increments that are mixed to form a single sample for analysis, or *flow-weighted*, collecting individual samples of varying amounts based on volume, flow and time requirements that are combined to form a single composite sample (GC&WWE, 2009; NRCNA, 2009).

Automatic samplers or manual "grab" samples are used to collect composite samples for determining an overall average or event mean concentration (EMC) for a particular sampling point(s) (USEPA, 1999a). The automated sampling technique uses electronic or mechanical devices to collect the actual stormwater sample, whereas manual sampling involves collecting samples and flow measurements by personnel using hand-operated equipment. For laboratory analysis, the Urban Stormwater BMP Performance Monitoring Manual (GC&WWE, 2009) recommends consulting Federal Register 40CFR136.3 for procedures on sample containers, preservatives and maximum holding times to be used for the specific constituents being tested. The type and scale of the monitoring program, duration, number of precipitation events, logistics, cost and personnel are all important factors to consider when developing the method of water quality collection.

The analysis of the performance data of stormwater BMPs and LID practices is often complex and challenging due to the variety of metrics or measures available to assess and quantify the amount of a constituent conveyed to and from the stormwater treatment practice. Pollutant concentrations, loads and EMCs are three primary measures commonly used (GC&WWE, 2009). Concentrations are generally measured at particular points in time; total loads are typically calculated over a specific duration (e.g., individual storm, daily, weekly); and, EMCs can be used to estimate the pollutant loading from a given storm. The EMC approach allows for the analysis of wet weather flows at a particular site and provides a useful means for quantifying the pollution level resulting from a runoff or snowmelt event (GC&WWE, 2009). In addition, runoff volume reduction is directly associated with contaminant load reduction, and therefore is also a key metric used to quantify performance of stormwater treatment practices that store, infiltrate and evapotranspire captured runoff (GC&WWE, 2009). Runoff volumes are typically based on continuous flow measurements taken at well-defined inlets and outlets. Where this is not feasible, model simulations may be used to approximate inflow and outflow volumes in order to estimate volume reductions.

Data Analysis

Another critical component in establishing a comprehensive water quality monitoring program is to understand how the monitoring data will be analyzed and evaluated. Based on the type of stormwater BMP or LID practice, numerous methods are available to evaluate the performance of the stormwater treatment practice. Quantifying the efficiency of a stormwater BMP or LID practice in removing or reducing pollutants contained in urban runoff has generally focused on methods that examine and compare "percent removal" (GC&WWE, 2009). However, the USEPA (1999a; 2002) and the Urban Stormwater BMP Performance Monitoring Manual (GC&WWE, 2009) report that using percent removal alone may not provide an adequate assessment of performance (Strecker et al., 2000; Li and Davis, 2009) for the following reasons (GC&WWE, 2007):

- Percent removal is primarily a function of influent quality. Stormwater BMPs, LID and bioretention typically function at different percentages across a wide range of influent water quality concentrations. When loads and performance are linked to low influent concentrations, the percentage of pollutant removal is usually low, while heavily polluted influent conditions generally result in larger percentage removals (USEPA, 2002).

- Significant variations in percent removal may occur for treatment practices providing consistently good effluent quality.

- Treatment practices with high percent removal may have unacceptably high concentrations of pollutants in the effluent, which can lead to a false determination that the treatment practice is performing well, when it may not be.

- Percent removals do not adequately reflect the effect of volume reduction.
- Methods for calculating percent removal are inconsistent (e.g., event by event, mean of event percent removals, inflow to outflow median, inflow to outflow load, slope of regression of loads/concentrations). Very different percentages can be reported from the same data set.
- No allowance in the method for outliers to assess uncertainty in the reported value.

For the reasons listed above, percent removal data is not presented in the International Stormwater BMP Database. Instead, the International BMP Database Project Team recommends using an approach that focuses on: (1) how much the BMP reduces runoff volumes, (2) how much runoff is treated (versus bypassed), (3) whether the BMP can demonstrate a statistical difference in effluent quality compared to influent quality, (4) what distribution of effluent quality is achieved, and (5) how well the BMP reduces peak runoff rates, especially for smaller, frequent storms (GC&WWE, 2007).

Monitoring is an important aspect of a stormwater management program, but it is also the most challenging which makes formulating a monitoring program no easy task. In fact, several factors must be considered before a sample can be collected – mode of sample collection, compositing the sample or not, water quantity and water quality parameters, metric of analysis, computation method and data reporting. The Urban Stormwater BMP Performance Monitoring Manual is a valuable resource to consult when developing a stormwater monitoring program. The need for consistent analysis methods is essential to ensure accurate reporting metrics are presented in the research, and to ensure that state and local governments are basing decisions to use stormwater BMPs and LID practices on accurate data.

To evaluate the effectiveness of a stormwater BMP or LID practice, a typical 1-2 year monitoring program may be established and designed to target removal of a specific pollutant/nutrient, like phosphorus for example. At a minimum, grab samples could be manually collected by volunteers at specified inflow and outflow points during the "first flush" of each storm event to determine the concentration levels of phosphorus leaving the stormwater treatment system. To measure runoff volume and contaminate load reduction of a stormwater BMP or LID practice, a more elaborate monitoring program is needed. In this case, automated samplers would be required to obtain flow-weighted composite samples and accurate flow measurements at well-defined inlet and outlet locations to quantify phosphorus load reduction of the stormwater control. These samples would be collected throughout the storm hydrograph (rising limb, at or near peak discharge, and falling/recession limb).

Mathematical Stormwater Models

In addition to statistical analysis based on field data, numerous mathematical stormwater models have been designed to estimate the impacts of stormwater discharges on receiving waterbodies, both from a water quantity and water quality perspective. The models listed in Table 2-4 are examples of the many methods that have been developed for a variety of applications, ranging from small urban catchments to urban pollutant loading at a range of watershed scales. These stormwater models and models supporting the evaluation of stormwater control measure (SCM) design and effectiveness are based on simulating a mass budget of water and for specific pollutants (NRCNA, 2009).

Table 2-4: Examples of Mathematical Models for Stormwater Modeling (NRCNA, 2009)

Model	Common Use	Typical Scale	Complexity	Data Requirements	Stormwater Control Measure (SCM)	Source
Generalized Watershed Loading Function (GWLF)	Rural/urban runoff, pollutant loading	Medium to watershed	Simple to medium	Land use, soil texture, precipitation time series	Runoff reduction with Curve Number modification	http://www.avgwlf.psu.edu/overview.htm
Model for Urban Stormwater Improvement Conceptualization (MUSIC)	Urban runoff, pollutant loading, hydraulic design, simple receiving water	Small to large	Medium to complex	Land use, soil texture, precipitation, drainage system, SCM type and sizing	Comprehensive evaluation of SCM systems	http://www.ewater.com.au/products/ewater-toolkit/urban-tools/music/
Storm Water Management Model (SWMM)	Urban runoff, pollutant loading, hydraulic design	Small to large	Medium to complex	Land use, soil texture, meterological time series, drainage system, SCM type and sizing	Infiltration practices	http://www.epa.gov/ednnrmrl/models/swmm/
PCSWMM	Urban runoff, pollutant loading, hydraulic design	Small to large	Medium to complex	Land use, soil texture, meterological time series, drainage system, SCM type and sizing	Enhanced SCM compared to SWMM	http://www.chiwater.com/Software/PCSWMM.NET/index.asp
Source Loading & Management Model (WinSLAMM)	Urban runoff, pollutant loading	Small to large	Intermediate	Land cover, land use, development characteristics, soil texture, compaction, rainfall event time series, SCM type and sizing	Comprehensive evaluation of SCM systems	http://www.winslamm.com/winslamm_updates.html
Soil & Water Assessment Tool (SWAT)	Rural runoff, loading	Medium to watershed	Intermediate	Land cover/land use, soil texture, precipitation, temperature, humidity, solar radiation	Impoundments, agricultural conservation practices, nutrient management buffers	http://swatmodel.tamu.edu/
Hydrological Simulation Program - Fortran (HSPF)	Comprehensive watershed evaluation, receiving water dynamics	Medium to watershed	Complex	Land cover/land use, soil texture, precipitation, temperature, humidity, solar radiation	Infiltration practices	(USGS) http://water.usgs.gov/software/HSPF/ (USEPA) http://www.epa.gov/ceampubl/swater/shpf/

Models capable of simulating water quality results often require event mean concentration (EMC) data. Some of these models also have a simple "build-up/wash-off" approach to water quality simulation – SWMM (Storm Water Management Model), WinSLAMM (Source Loading and Management Model) and MUSIC (Model for Urban Stormwater Improvement Conceptualization), while other models simulate more complex geochemistry – SWAT (Soil & Water Assessment Tool) and HSPF (Hydrologic Simulation Program – Fortran) (NRCNA, 2009). For instance, the SWMM model integrates BMP hydrological modeling with associated treatment performance, but requires users to input their own BMP removal efficiency (Scholes et al., 2008), which in the absence of field data would need to be estimated. For specifically addressing the role of BMPs, like bioretention, into stormwater management strategies, MUSIC models BMP performance using algorithms to predict pollutant removal rates for TSS, TP and TN (Scholes et al., 2008). However, the National Research Council of the National Academies (NRCNA) considers MUSIC more of a planning tool as the model does not contain detailed hydraulic information required for routing and sizing of BMPs (2009). SWAT and HSPF are watershed models based on similar land-use runoff and loading factors that use detailed descriptions of interception, infiltration, runoff, routing and biogeochemical transformations (NRCNA, 2009). Both models were developed prior to the availability of detailed digital spatial information on watershed form, and therefore use conceptual control volumes that are not spatially linked to model watershed hydrology (NRCNA, 2009).

With the advent of higher-resolution digital topographic and land-cover data, new sets of models are being developed that quantitatively predict downstream impacts in urbanized watersheds based on spatial simulations. While these models are not yet operational or widely used, they have the potential to directly link stormwater generation with specific dischargers, but the challenge of scaling to larger watersheds still remains (NRCNA, 2009). These models require further investigation and testing to demonstrate their capabilities in supporting stormwater management.

Experimental Field Studies

The effectiveness of stormwater BMPs, LID and bioretention can be measured by the actual improvement in water quality as a result of implementing the stormwater treatment practice (USEPA, 1999a; GC&WWE, 2009) with respect to their ability to remove pollutants from runoff and their hydraulic performance capability, i.e., peak discharge rates and total volume reduction (USEPA, 1999a). Given the distributed nature of stormwater controls and treatment practices, approaches for monitoring LID must be carefully developed in order to provide meaningful results. Most LID studies have focused on monitoring an individual LID practice, like a bioretention cell or rain garden, to identify and understand the processes governing treatment and to assess the performance of the individual practice. Since many stormwater BMPs and LID strategies are designed to treat runoff from small storms, rather than large storms (GC&WWE, 2009), it is important to understand the basis of design for stormwater BMPs and LID practices prior to developing monitoring programs to accurately evaluate their performance.

Evaluating LID at the site level poses additional challenges when collecting samples in that there may not be clearly defined inlet and/or outlet locations as stormwater controls are distributed over a wider area, and because natural hydrologic functions are occurring within the treatment practices themselves (GC&WWE, 2009). In this case, performance can be assessed by comparing hydrologic and water quality characteristics from the LID site to one or more reference watershed conditions (GC&WWE, 2009). To obtain sufficient results and draw appropriate conclusions about the performance of the site-level LID practices, a 5-10 year monitoring period is recommended (Clausen, 2007), as evidenced by the Jordan Cove Watershed Project reviewed in Chapter 4.

Performance monitoring of stormwater BMPs and LID practices provide documented evidence as to the effectiveness of the system in controlling stormwater runoff and mitigating the effects of NPS pollution. Table 2-5 presents six field experiments that monitored the performance of bioretention systems. Two of these experiments were unique in that one concentrated on evaluating LID practices at the site level, while the other was a retrofit application. Monitoring efforts consisted of evaluating the capabilities of the treatment practices in reducing the volume of stormwater runoff from buildings, parking lots and streets, as well as water quality performance. The length of the monitoring periods varied from 10 months to 10 years amongst the studies, and covered a total period of 1995 - 2007. These studies were conducted for a multitude of reasons, consisting of hydrologic performance, pollutant attenuation, and improving field bioretention design and maintenance procedures. One key difference in the “SEA Street” in Seattle, WA study in comparison to the other experiments is that no underdrains or liners were used.

The results of the LID and bioretention field experiments noted in Table 2-5 demonstrate the effectiveness of the treatment practices in retaining large volumes of runoff and pollutants on site, which consistently reduces concentrations of certain pollutants and intrinsically links hydrologic performance with the benefits of water quality. For example, the College Park, MD and Seattle, WA studies reported average flow reductions of 44–74% with significant delays in flow peaks (Davis, 2008; Chapman and Horner, 2010). Substantial decreases in outflow volumes correlated to high mass removal rates for heavy metals recorded in all sites. However, this research also shows that retention of phosphorus and nitrogen were problematic in the Connecticut and North

Carolina field experiments (Dietz and Clausen, 2006; Li and Davis, 2009; Hunt et al., 2006). In the Haddam, CT rain garden study, mulch was the source of the increase in total phosphorous (Dietz and Clausen, 2006), whereas a high P-index in the soil of a bioretention cell in Greensboro, NC caused the outflow to be greater than the inflow (Hunt et al., 2006). These results suggest that current bioretention design standards may not be effective when it comes to reducing phosphorus and nitrogen loads. Refinement to the guidance is needed specifically in the area of soil media depth, area and content, to further improve water quality performance.

Table 2-5: Bioretention Experimental Studies & Results

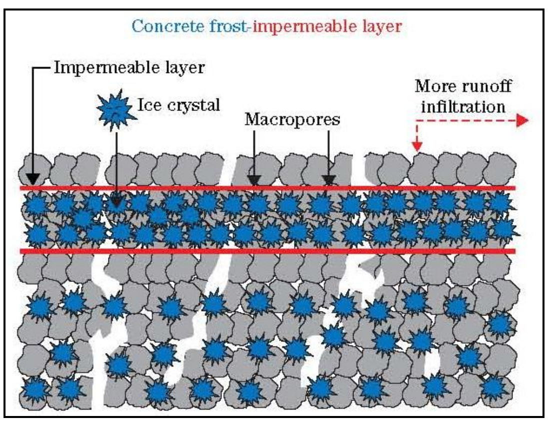
Conducted By & Site Location	Period of Study	Type of System	Purpose of Study	Method of Evaluation	Results	Source
University of Connecticut (Haddam, CT)	2-year period (2002 - 2004)	2 Rain Gardens; equipped with liners & underdrains	Year 1 - Evaluate the ability of field-installed rain gardens to retain pollutants and reduce volume in roof runoff. Year 2 - Evaluate the effect of a saturated zone in a rain garden on pollutant concentrations in roof runoff.	**Year 1:** Subsurface & overflow samples collected. Weekly composite samples analyzed for TP, TN, & monthly analysis for Cu, Pb & Zn. Analysis of Variance (ANOVA) method and % pollution retention based on mass balance used to compare nutrient concentration retention between inlet & underdrains. **Year 2:** Mulch & plant samples taken in addition to Year 1 samples. In addition to Year 1, paired watershed approach using Analysis of Covariance (ANCOVA) method to analyze the effect of the saturation treatment.	**Year 1:** 1"-sized storage capacity provides good runoff control, but TN only nutrient well-retained by rain gardens. **Year 2:** High retention of flow, significant reduction of TN due to saturation treatment. Mulch found to be a sink for metals, nitrogen and phosphorus.	Dietz & Clausen (2005; 2006)
University of Maryland (College Park, MD)	Summer 2003 - Fall 2004	2 Bioretention Facilities; equipped with liners & underdrains	Quantify water quality improvements & reduction of hydrologic flow peaks & volume in 2 parallel bioretention cells received from parking lot runoff.	Automatic sampler collected discrete flow-weighted composite inlet and outlet samples over 12 storm events. TSS, TP, TN, Cu, Pb and Zn analyzed by EMC method and probability plots.	In all cases, the median pollutant output was lower than the input indicating successful water quality improvement. The bioretention media captured the entire inflow volume for 18% of the monitored events, with no outflow. Mean peak reductions were 49% & 58% for two cells and flow peaks were delayed.	Davis (2007; 2008)
University of Maryland (College Park & Silver Springs, MD)	15-month period (April 2006 - July 2007)	2 Bioretention Facilities; equipped with underdrains	Examine water quality performance to improve field bioretention design and maintenance procedures.	Monitoring equipment & automatic samplers used to measure flow rate & collect water samples at inflow & outflow points of each bioretention cell. Flow weighted composite samples were analyzed for pollutant levels (TSS, oil & grease, organic carbon, TP, TN, Cu, Pb and Zn) to obtain the pollutant mean concentration (EMC) for the events and graph probability plots.	Both bioretention cells effectively removed TSS, Pb and Zn from runoff through concentration reduction. All but TOC showed pollutant reduction. Effluents had good water quality except nitrate, copper and phosphorus due to media organic matter dissolution.	Li & Davis (2009)
North Carolina State University (Chapel Hill & Greensboro, NC)	10-12 month periods (June 2002 April/May 2003)	3 Bioretention Facilities; equipped with underdrains	Examine pollutant removal abilities and hydrologic performance in bioretention.	Paired watershed study to compare TN and TP pollutant load reductions in different media mixtures. Automatic samplers collect flow-composite samples at inflow and outflow. Annual pollutant mass inflow and outflow measured.	Bioretention mass removal rates for TP varied (up & down) due to different media mixes. High degree of metal mass removals occurred. Significant reduction in outflow runoff volume. Outflow nutrient concentrations typically exceeded those of inflow for TP and TN.	Hunt et al. (2006)
University of Washington ("SEA Street" in Seattle, WA)	Flow measurements: Oct. 2003 - March 2006; Water quality sampling: Dec. 2004 - March 2006	Street-Drainage Bioretention System; no underdrain	Evaluate a street-drainage bioretention system for its ability to reduce runoff volume and pollutants.	Event-based, flow-paced composite samples collected at inlet and outlets. Method of analysis: pollutant removal efficiency defined by the mass balance equation weighing the EMCs according to runoff volumes in the composite samples.	48-74% of incoming runoff was lost to infiltration and evaporation. Outlet pollutant concentrations were significantly lower than inlet for all constituents except Cu. Motor oil most effectively removed.	Chapman & Horner (2010)
University of Connecticut (Jordan Cove Watershed Project in Watertown, CT)	10-year period: calibration (1995 - 1998), post-development (2002 - 2005)	LID System - open space, grassed bioswales, pervious paver road, bioretention system at cul de-sac, individual rain gardens on each lot, shared driveways, cluster housing	Quality and quantity of residential stormwater runoff from a control, traditional and LID watershed were compared in a paired watershed study.	Discharge & overland flow monitored. Flow-weighted composite collected weekly for nitrates, TKN, TP, TSS, Cu, Pb and Zn. Grab samples collected for any discharge occurring during site visits (FC & BOD). Statistical Methods: ANCOVA, paired t-tests, mass exports, predicted means & % change.	LID outperformed traditional methods: storm and peak flows reduced; decreased mass exports of TKN, nitrates, Pb, and Zn; increased concentrations and exports in TSS and TP in grassed swales (fertilizers) because stormwater was directed through them.	Bedan & Clausen (2009)

Challenges of Cold Weather

The volume of precipitation, temperature differences and timing of storm events are all important factors that contribute to water quality problems. In northern regions of the United States, like New England, the hydrological cycle becomes much more complex in urban areas during cold weather conditions. Snowpack accumulation results in the build-up of solids, nutrients and toxic materials from atmospheric deposition, road and vehicular deposition, the use of deicing and anti-skid agents and repeated freeze-thaw cycles (Oberts et al., 2000; USEPA, 2002; Marsalek et al., 2003; Muthanna et al., 2007). Consequently, greater concentrations of pollutants are stored in snowpacks and then released, at varying rates, during runoff and snowmelt events (Oberts et al., 2000; USEPA, 2002; Marsalek et al., 2003). As discussed previously, traditional conveyance methods of stormwater control were designed as highly efficient drainage systems, not as controls for managing urban runoff. As such, these conveyance systems are not meeting water quality standards. Therefore, state and local municipalities in New England need to employ innovative stormwater practices to not only manage the substantial volume of urban runoff, but also to treat large amounts of pollutants that are released from rain-on-snow events and snowmelt conditions (USEPA, 2002; Oberts, 2003) before reaching surface waterbodies.

Widespread adoption of stormwater management practices such as LID and bioretention is hampered by the perception that these systems exhibit reduced performance in cold climate, both for water quality treatment and hydraulic efficiency resulting from “frozen filter media and dormant biological functions” (Roseen et al., 2009). Nevertheless, much of the research suggests that these systems do continue to infiltrate and reduce pollutant loads during the winter season, but to varying degrees. For example, the University of New Hampshire Stormwater Center (UNHSC) has been monitoring LID practices, such as bioretention cells, surface sand filters, porous asphalt and tree filters, since 2004. Their research emphasizes performance of these practices in cold climates based on filter media frost penetration and hydraulic efficiency in comparison to warmer conditions. Although seasonal variation and frost penetration was observed, the impact of cold weather was not substantial enough to affect hydraulic efficiency and performance in the LID systems (Roseen et al., 2009). A frost penetration cycle was observed during the winter monitoring periods that included frost penetration into the filter media prior to rain and snowmelt events which served to thaw the frozen filter media, followed by repeated frost penetration in subsequent below freezing days (Roseen et al., 2009).

More than the presence/absence or depth of frost, LeFevre et al. (2009) cite the type of soil frost as the factor most influencing the infiltration capacity of bioretention performance, which therefore, potentially inhibits the reduction of pollutant loads. Soil frost can significantly reduce the infiltration capacity through soil, break down soil aggregates and decrease the strength of the soil (USDA, 2009). More specifically, the infiltration capacity and type of soil frost are largely determined by the moisture content of the soil when it freezes (Brooks et al., 2003). For example, *concrete frost* occurs when saturated soil freezes, creating an ice lens or impermeable layer through which little to no water movement is possible (Figure 2-8) (Brooks et al., 2003; Muthanna et al., 2007; LeFevre et al., 2009). In bioretention systems, saturated soil medium that is not insulated by snow cover could be subject to concrete frost formation (with a very limited infiltration capacity). In contrast, *granular frost* conditions occur when unsaturated porous soil freezes with very little soil moisture and reduction in infiltration rates (Figure 2-9) (Brooks et al., 2003; Muthanna et al., 2007; LeFevre et al., 2009). In particular, a coating of ice or frost formed on large soil particles has the effect of increasing their diameter and decreasing the corresponding pore space and permeability (USDA, NRCS, 2011). However, if the soil pore space and permeability are still high, i.e., greater than rainfall intensity or snowmelt rate, then infiltration should be unimpeded. This suggests that the upper soil layers of bioretention systems may possibly yield very high design values for infiltration capacity.



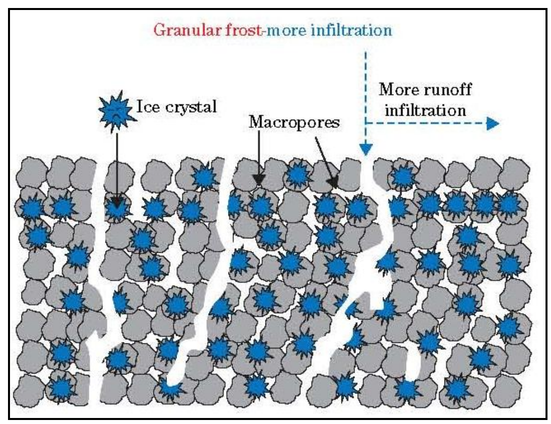


Figure 2-8: (Left) Conceptual Diagram of Concrete Frost (USDA, 2009)
Figure 2-9: (Right) Conceptual Diagram of Granular Frost (USDA, 2009)

Soil frost is also affected by vegetative cover, soil texture, depth of organic matter and snow depth (Brooks et al., 2003). However, the composition of bioretention media is likely the reason that "infiltration continues to occur despite frozen conditions as rapid thawing of the soil media occurs when runoff enters the bioretention area" (Dietz, 2007). Novotny (1986) explains that infiltration of substantial volumes of meltwater can occur into clay and loam soils, as well as sands, if an impermeable layer does not form before snow cover.

Northern climate zones present many challenges in controlling the adverse effects of snowmelt during the winter season. The studies presented in Table 2-6 evaluated and/or monitored the performance of bioretention and various LID practices during cold weather conditions; all four studies evaluated the infiltration capacity of the systems, while just two of the studies monitored water quality performance. These studies support the use of LID systems, and concluded that bioretention systems continue to infiltrate in cold climate conditions (Emerson and Traver, 2008; LeFevre et al., 2009; Roseen et al., 2009). Well-draining soil media was critical to the functioning of the bioretention systems in the Minnesota study (LeFevre et al., 2009); while pollutant reduction of heavy metals was most notable in the top mulch layer of the bioretention systems in the Norwegian study (Muthanna et al., 2007). Less metal retention was found in plant uptake, but overall, biological functions, i.e., plants, continued to foster the infiltration and reduction of effluent loads during the winter (Muthanna et al., 2007; Roseen et al., 2009). As in the case of snowpack, vegetative cover acts as an insulator that inhibits the likelihood of soil frost. Roseen et al. (2009) reported that the LID systems at UNHSC outperformed conventional structural BMPs and proprietary manufactured systems with respect to urban hydrology and contaminant removal efficiency. Total suspended solids (TSS) and heavy metal reductions of 95% and 89-99% were recorded in the UNHSC and Norwegian studies, respectively (Muthanna et al., 2007; Roseen et al., 2009); while phosphorus and nitrogen loads showed poor results for the bioretention cells at UNHSC, regardless of the season (Roseen et al., 2009). The results of these bioretention studies show great promise in managing urban runoff and retention of pollutants from snowmelt conditions and should alleviate many of the concerns related to reduced winter performance, however, more studies and/or design guidance are needed to improve pollutant load reductions for phosphorus and nitrogen.

Table 2-6: Cold Climate Experimental Studies & Results

Study Conducted By	Location	Period of Study	Type of System	Purpose of Study	Results	Source
Norwegian University of Science & Technology	Trondheim, Norway	February & March 2006	2 Bioretention Systems	Evaluate retention of heavy metals during snowmelt conditions using snow from low, medium and high density traffic roadways.	Small-scale bioretention cells were successful in treating snowmelt from urban roads: metal retention - mass reductions in zinc, copper, lead and cadmium in the 89-99% range, and a decrease in outflow concentrations ranging 81-99%.	Muthanna et al. (2007)
Villanova Urban Stormwater Partnership at Villanova University	Villanova, PA	2-year period	Bioinfiltration Traffic Island & Pervious Concrete Infiltration Basin	Monitor variations in infiltration processes to determine long-term and seasonal changes that may be relevant to infiltration BMPs.	The analysis of continuous monitoring indicates that both BMPs showed considerable seasonal variation but exhibited no evidence of systematic decrease in performance for the period monitored.	Emerson & Traver (2008)
Dakota County Soil & Water Conservation District	Twin Cities, MN region	3 winter seasons: 2005-2008	4 Bioretention Systems	Evaluate cold climate hydrologic performance under snowmelt conditions.	Measured responses from the bioretention cells reveal that the hydrologic function was maintained in the cold weather, and that rapid infiltration occurred in many cases.	LeFevre et al. (2009)
University of New Hampshire Stormwater Center	Durham, NH	2-year period: 2004-2006	15 Treatment Strategies: 6 LID Systems, 3 Conventional Structural BMPs & 7 Proprietary Manufactured Systems	Monitor, compare and contrast systems over 27 rainfall-runoff events for filter media frost penetration, hydraulic efficiency and seasonal variations of pollutant removal effectiveness.	Performance evaluations indicate that LID designs have a high level of functionality during winter months, and that frozen filter media do not reduce performance.	Roseen et al. (2009)

Summary

A fair amount of research currently exists on the usage of green infrastructure and LID practices such as bioretention, as agents for managing stormwater. Many approaches and guidelines are available for selecting the most appropriate stormwater BMP or LID practice for a particular site to control stormwater runoff. Typically, these recommendations focus on siting location, soil type, design area and depth, storage capacity, operation and maintenance requirements, and cost. At present, however, design guidance is not available for determining the type of stormwater treatment practice that improves water quality for removal/reduction of a particular pollutant of concern.

There are gaps in the research as noted throughout this chapter that include establishing an industry standard model that accurately measures runoff and pollutant reductions resulting from LID applications like bioretention, as well as long-term studies that demonstrate how LID practices perform over longer periods of time. Additional research areas identified by Dietz (2009) include investigations on the effect of different media mixtures for bioretention to minimize the risk of phosphorus export, as well as the ability of LID systems to retain and destroy bacteria and viruses. Davis et al. (2009) also conclude that more efficient design guidelines can be developed for water quality, water quantity and life cycle costs if further research is conducted in the areas of quantitative design and performance information.

To summarize the main findings of this literature review and to promote further research in this area, a conceptual framework linking green infrastructure/LID practices and performance evaluation is developed in the succeeding chapters, as well as further analysis of the International Stormwater BMP Database and National Pollutant Removal Performance Database. This framework describes the necessary steps involved to develop a green infrastructure/stormwater treatment scenario that promotes the increased usage of bioretention based on pollutant removal performance metrics. The assessment method described in the conceptual framework provides the necessary steps to make recommendations for design guidance and future applications of monitoring practice(s).

CHAPTER 3

A METHOD FOR ASSESSING THE EFFECTIVENESS OF BIORETENTION TO IMPROVE WATER QUALITY

The purpose of this study is to explore and evaluate the efficacy of one specific green infrastructure practice for improving water quantity and quality in order to demonstrate to local governments if green infrastructure is an appropriate method of protecting waterbodies from the negative impacts of nonpoint source (NPS) pollution. Therefore, the method for assessing the effectiveness of bioretention for its ability to improve water quality is the focus of this chapter. The primary focus of this methodology is on the process used for the assessment which includes specific goals for stormwater management and water quality, selection of target metrics for analyzing various monitoring methods, and an evaluation of these monitoring methods that could potentially be applied at the state or local government level in New England urban environments.

Overview of the Methods

An extensive literature review on the subject of performance assessment and monitoring of green infrastructure/stormwater treatment practices was conducted. This review revealed that an industry standard model to accurately measure runoff and pollutant reductions, resulting from LID applications like bioretention, needs to be established. In addition, the body of research studied highlights a number of themes relating to water quality that were consistently referenced throughout, such as consistent collection parameters, sampling techniques, analysis methods and reporting requirements.

These themes were used to assess the monitoring methods and are the basis of the conceptual framework developed in Figure 3-1. A parallel structure was also developed in Figure 3-2 to further examine the monitoring methods. The conceptual framework and parallel structure also help to further link the fields of landscape architecture, natural resources management and various engineering disciplines (i.e., civil, environmental, hydraulic and hydrologic) by integrating a scientific assessment into urban planning and design process. The proposed method addresses the need to gather sufficient technical design and performance monitoring and reporting information to improve the selection of stormwater BMPs and LID practices in order to effectively address local stormwater concerns – water quality.

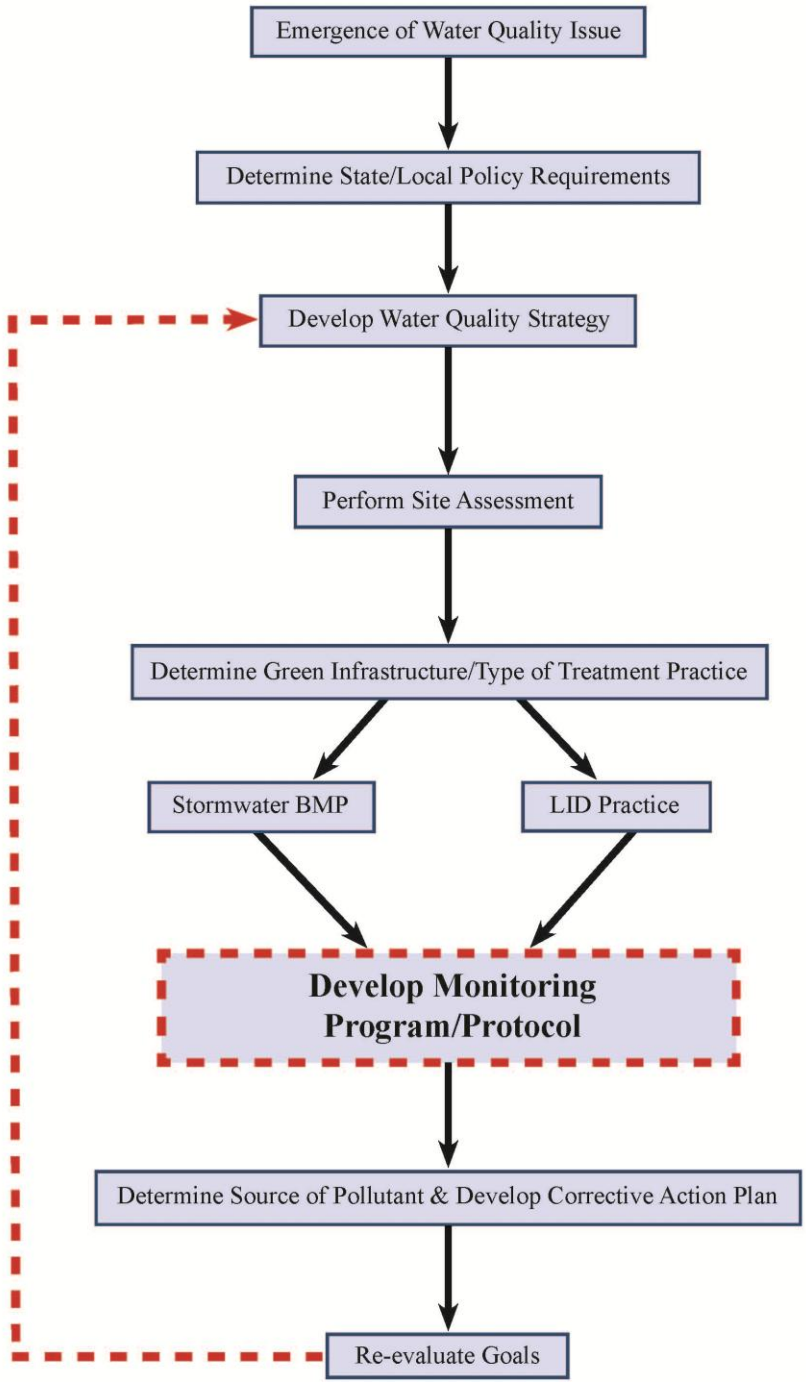


Figure 3-1: Conceptual Framework for Assessing the Effectiveness of Bioretention to Improve Water Quality

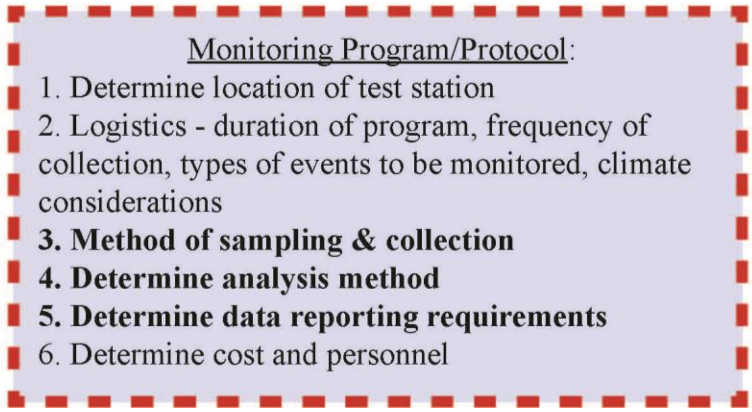


Figure 3-2: Parallel Structure for Further Examination of Monitoring Methods

To obtain a more advanced understanding of the monitoring methods used to evaluate performance of bioretention in New England urban environments, the primary methods used to achieve the stated goals and objectives of this study are as follows:

1. Document the protocols, guidelines and requirements necessary to aid state and local governments in the selection of performance monitoring methods, with specific emphasis on sample collection, method of analysis and data report requirements. The Urban Stormwater BMP Performance Monitoring Manual (GC&WWE, 2009) recommended by the USEPA and the Center for Watershed Protection (CWP) Guidance to Develop Stormwater Monitoring Programs (2008) are the primary references.

2. Analyze the monitoring methods used by industry experts to determine pollutant removal performance. The International Stormwater BMP Database established by the American Society of Civil Engineers (ASCE) and United States Environmental Protection Agency (USEPA), and the National Pollutant Removal Performance Database managed by the Center for Watershed Protection (CWP) will serve as the basis of this analysis.

3. Evaluate the monitoring methods of two bioretention case studies in relation to urban environments in New England – the Jordan Cove Watershed Project in Watertown, CT and the field research site at the University of New Hampshire Stormwater Center in Durham, NH.

Based on the above methods, a correlation analysis of the monitoring methods will be performed in Chapter 4 to compare industry standard databases, research studies and case studies in terms of research design, similarities and differences, and key findings that influence and/or support bioretention design and monitoring practices, as well as the contribution to the profession of Landscape Architecture. The final product in Chapter 5 will yield recommendations for design guidance and future applications of monitoring practice(s).

CHAPTER 4

APPLICATION

Monitoring Protocols

In order to measure the effectiveness of stormwater BMPs and LID practices for their ability to improve water quality, developing a comprehensive monitoring plan is an essential first step. The primary sources for information regarding monitoring programs/protocols are the Urban Stormwater BMP Performance Monitoring Manual (GC&WWE, 2009) recommended by the USEPA and the Center for Watershed Protection (CWP) Guidance to Develop Stormwater Monitoring Programs (2008). These sources were used to document the protocols, guidelines and requirements necessary to aid state and local governments in the selection of performance monitoring methods, with specific emphasis on sample collection, method of analysis and data report requirements.

The United States Environmental Protection Agency (USEPA, 2006b) established a eight step process that provides a systematic approach for the collection of stormwater data to evaluate the effectiveness of stormwater BMP and LID practices (Figure 4-1), and is the approach recommended in the Urban Stormwater BMP Performance Monitoring Manual. In the CWP Guidance to Develop Stormwater Monitoring Programs, the manual recommends a nine step process as guidance for developing and implementing a stormwater monitoring program, and is outlined in the Figure 4-2. The CWP takes a unique approach by using six monitoring studies as examples to develop local stormwater monitoring programs. The target audience is municipal separate storm sewer system (MS4) communities, but this guidance could also be used in other municipalities, state and federal agencies, universities and watershed organizations that are responsible for implementing stormwater management programs and practices. The six monitoring study design applications are (CWP, 2008):

- Quality of stormwater at the outfall
- Source area monitoring
- Performance monitoring of individual stormwater treatment practices
- Implementation and longevity surveys of stormwater treatment practices
- Monitoring public education programs to improve water quality
- Cumulative effect of treatment at the catchment scale

The processes identified by the USEPA and CWP for developing a stormwater monitoring plan are essentially the same. Two differences were noted. In the USEPA recommended approach, feedback step has been incorporated into the process to reevaluate the goals and objectives of the program and to make any necessary alterations to the plan accordingly. The CWP approach advocates for the review of existing research studies and databases early in the process to evaluate industry standards and current monitoring methods in order to make sound decisions in the development of monitoring programs. Both steps have merit and should be incorporated into the process of developing a stormwater monitoring plan.

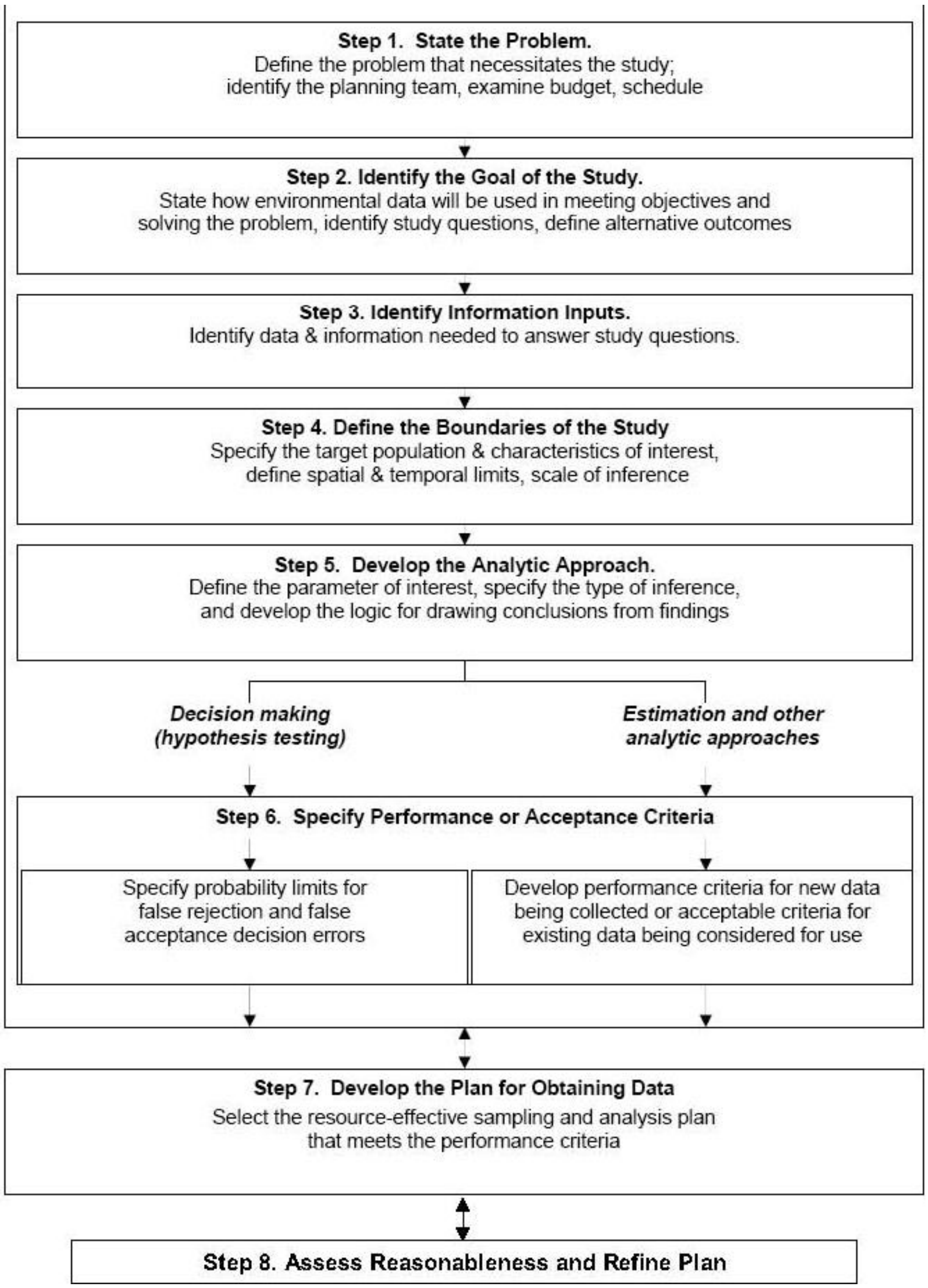


Figure 4-1: Eight Step Systematic Approach to Developing a Monitoring Plan (USEPA, 2006)

<u>Stormwater Monitoring Program</u> (Center for Watershed Protection)

1. Define monitoring objective(s)
2. Review existing studies and databases
3. Select study design
    a. Define scope
    b. Approach to study design
4. Determine data and resource needs
    a. Monitoring parameters
    b. Sample size and frequency
    c. Personnel (in-house staff, volunteers, consultants)
    d. Budget
5. Select study site
    a. Factors to be considered when selecting site
    b. Data requirements to characterize site/drainage area conditions
6. Develop monitoring plan
    a. Sampling techniques and equipment
    b. Data management and quality control considerations
    c. Monitoring problems
    d. Resources to consult
7. Collect field data
8. Perform lab analysis
9. Evaluate data and draw conclusions

Figure 4-2: Nine Step Process for Developing and Implementing a Stormwater Monitoring Program (CWP, 2008)

Understanding the purpose of the stormwater monitoring study is critical to the success of the monitoring program and will dictate the method used to measure performance. Several strategies have been employed in urbanized watersheds to improve water quality, including: (1) setting pollutant reduction levels to control the release of mass pollutants into receiving waters; (2) establishing maximum pollutant levels for new development; (3) using annual flow volumes for stormwater management designs that focus on annual rainfall volumes and associated pollutant loads ; (4) basing stormwater management designs on first flush principles that capture a specific rainfall amount; and, (5) developing designs using stormwater treatment practices that achieve pollutant removal targets or water quality control measures (USEPA, 2002). These strategies highlight the varying degrees at which water quality can be monitored, and provides some insight into the different types of monitoring used to evaluate the effectiveness of stormwater quality controls.

Multiple sampling methods are available for the collection and compositing of stormwater samples. The first distinction is in the mode of collection – grab sampling or automatic sampling. Table 4-1 documents the advantages and disadvantages of each method. Grab sampling is the most limiting of the two methods because it is personnel dependent and the results often show high variability. However, grab sampling can be useful for collecting discrete water samples for such constituents as bacteria or for discharges that may be occurring when observed during site visits (Clausen, 2007). Automatic sampling is the preferred approach for collecting samples as evidenced in the research and monitoring studies reviewed. However, the National Research Council of the National Academies (NRCNA) cautions that reliable data is compromised when the equipment malfunctions, or breaks down and is need of costly repairs (2009). The second important factor in the collection of stormwater samples is how and whether the samples are combined following collection. Sample compositing refers to flow- and time-weighted composite samples and was previously discussed in this study. Details of how water quality data is collected are important component of any monitoring plan, especially when monitoring multiple inlets, and employing a method that uses a combination of grab and automated methods for compositing samples. Local volunteers can be enlisted to aid in collecting samples.

Table 4-1: Advantages and Disadvantages of Sampling Methods (CWP, 2008)

Type of Sampling Method	Advantage	Disadvantage
Manual	Low capital cost	High cost of labor
	Not a composite	Inconsistency in collection
	Point-in-time characterization	Probability of increased variability due to sample handling
	Can collect extra samples in short time when necessary	Repetitious and monotonous task for personnel
	Note unusual conditions	
	No maintenance	
	Compensate for various situations	
Automatic	Consistent samples	Inflexibility
	Minimal labor requirement for sampling	Restricted in size to the general specifications
	Probability of decreased variability caused by sample handling	Sample contamination potential; Subject to damage by vandals
	Has capability to collect multiple bottle samples for visual estimate of variability and analysis of individual bottles	Considerable maintenance for batteries and cleaning; susceptible to plugging by solids

When evaluating stormwater controls, there are four main metrics to consider: concentration, volume, total mass/load and event mean concentration (EMC). Table 4-2 provides a definition of each metric. Concentration levels are primarily needed for calculating the total mass/load of a particular pollutant and are the basis for EMC efficiency calculations. This metric is useful when trying to meet specific water quality objectives, and in determining whether a target pollutant is leaving the treatment practice. Runoff volume is a key component of the mass balance equation and is calculated by collecting flow measurements at the inflow and outflow locations of the treatment practice. Mass/loads are calculated by multiplying the average concentration and the total flow volume over the entire storm period. EMC is a statistical parameter used to quantify the pollution level that averages the inflow and outflow concentrations for all storms, but does not consider volume reduction in its calculation.

Table 4-2: Metrics Used for Performance Analysis (CWP, 2008; GC&WWE, 2009)

Metric	Definition	Comment
Concentration	Needed to calculate pollutant load	Measures stormwater at individual points in time
	Basis for EMC efficiency calculations	Can be useful for BMP efficiency evaluations (pollutograph)
Volume	Needed for mass balance equation	Key metric used to quantify BMP performance
	Based on continuous flow measurements over a specified duration	Volume reductions require inflow and outflow measurements
Mass/Load	Calculated using an average concentration X the total volume of flow over the averaging period	Avg. concentrations estimated by collecting flow and/or time weighted samples; flow data can be collected continuously, intermittently or modeled from hydrological info.
	(Many methods; contingent on sampling and flow measurements used at site)	Contaminant loads used when assessing impact to receiving waters; TMDLs (load & load reduction)
Event Mean Concentration	Defined as the total constituent mass / the total runoff volume	Statistical parameter to quantify the pollution level resulting from a runoff event
	Averages inflow & outflow concentrations for all storms	Does not account for volume reduction
		Primary focus of International Stormwater BMP Database & National Stormwater Quality Database

Quantifying pollutant removal performance can be calculated multiple ways. Two of the most commonly used analysis methods for reporting the effectiveness of stormwater BMPs and LID performance are pollutant removal efficiency and effluent quality. Table 4-3 documents these methods, the basis of calculation and pertinent information relative to each method. One analysis method frequently used by researchers is the Efficiency Ratio (ER) Method which is based on EMC data (GC&WWE, 2009). As previously discussed, quantifying pollutant removal efficiency based on EMC data evaluates only a portion of the overall performance or effectiveness of a stormwater BMP or LID practice because flow data is not figured into the equation. The Summation of Loads (SOL) Methods is endorsed by the Center for Watershed Protection and uses the total mass/load of constituents monitored over the entire study period. Flow data is used in this calculation method, but results may be dominated by a small number of large storms. The ER and SOL methods report pollutant removal efficiency as percent removal, which presents a summary of pollutant efficiency but does not look at removal statistically (GC&WWE, 2009).

Table 4-3: Methods of Analysis for Data Reporting Requirements (CWP, 2008; GC&WWE, 2009)

Efficiency Calculation Methods	Basis of Equation	Comments
Efficiency Ratio (EMC Efficiency) (Reported as % Removal)	Defined as the average EMC of pollutants over time	EMCs can be collected as flow-weighted composite samples/calculated from discrete measurements
	Need pollutant concentration for calculation	Weighs EMCs from all storms equally
		Unable to account for complexities of BMP designs
Summation of Loads (Mass Efficiency) (Reported as % Removal)	Defines efficiency based on the ratio of the sum all incoming loads to the sum of all outlet loads	Influenced by volume of water entering the BMP and water losses within the BMP
	Need flow, precipitation, pollutant concentration for calculation	Pollutant removal is most relevant over the entire period of analysis
		Water mass balance can be calculated to assure that inflows and discharges have adequately accounted for any gains/losses
		A small number of large storms can dominate efficiency
		Method endorsed by Center for Watershed Protection
Regression of Loads	Defines regression efficiency as the slope of a least squares linear regression of inlet and outlet pollutant loads, with the intercept constrained to "0"	The process of constraining the intercept of the regression line to the original is questionable and in some cases could be misrepresenting data.
		A few data points often control the slope of line due to clustering of loads about the mean storm size.
Mean Concentration	Unit minus the ratio of the average outlet to average inlet concentrations	Useful in measuring acute toxicity reduction from stormwater BMPs
		Weighs individual samples equally
		Method does not account for storage capacity
Efficiency of Individual Storm Loads	Calculates BMP efficiency for each storm based on the loads in and out.	Storm size or other storm factors are not considered in the average efficiency of the BMP
	The mean value of the individual efficiencies is used as the overall efficiency of the BMP	Weighs all storms equally; efficiency viewed as an average regardless of storm size
Effluent Probability	Mean concentration-based	Provides a statistical view of influent and effluent quality
		Endorsed by the International Stormwater BMP Database

The Effluent Probability Method is a uniform statistical approach based on water quality data and is used by the International Stormwater BMP Database to evaluate the effluent quality of stormwater BMPs and LID practices that are stored in the database. The authors of the Urban Stormwater BMP Performance Monitoring Manual recommend that the "Effluent Probability Method" be accepted by the stormwater industry as the standard for evaluating BMP studies. This method provides a statistical view of influent and effluent quality that is based on first determining whether the BMP is providing treatment (i.e., the influent and effluent mean EMCs are statistically different from one another) (GC&WWE, 2009). Next, a cumulative distribution function of influent and effluent quality or a standard parallel probability plot (GC&WWE, 2009) is examined to quantify BMP efficiency. The authors also recommend that a normal probability plot (Figure 4-3) be generated showing the log-transform data of the influent and effluent EMCs for all storms being evaluated for the BMP. This graphical analysis of water quality concentrations illustrates how well the data at the monitoring location is represented by the normal distribution; the mean and standard deviation of the normal distribution and the value of any specific quantile; the relationship between two distributions across the range of quantiles; the presence of any significant outliers; and, the width of the 95% confidence interval of the normal approximation (GC&WWE, 2009). This method also facilitates quantitatively comparisons of effluent concentrations that can be used to analysis performance across similar classes of treatment practices.

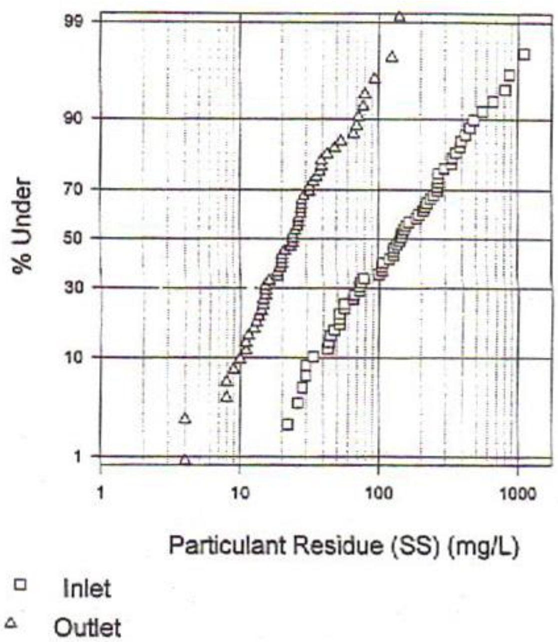


Figure 4-3: Example of Probability Plot for Total Suspended Solids (GC&WWE, 2009) (shows log transform of both inflow and outflow EMCs for all storms for the BMP)

Volume reduction is a key component of a mass-based equation and is essential in assessing the overall performance of stormwater BMPs and LID practices. Stormwater treatment practices, like bioretention, that have filtering, infiltration, biological uptake and storage capabilities have been shown to permanently remove some volume of runoff from the outflow. Therefore, volume reduction plays a pivotal role in the overall load reduction of a pollutant, which may not be immediately apparent if concentration numbers are compared. For example, when a stormwater treatment practice captures a portion of the incoming runoff and infiltrates it into the soil, pollutants in that portion of the runoff are effectively reduced, which ultimately minimizes the effect on downstream waterbodies. Therefore, a direct correlation can be drawn between volume and pollutant load reduction. If a BMP reduces the volume of runoff, it is said to have also reduced the pollutant load. Concentration-based analyses do not account for volume reduction, and as a result, may be understating performance results (CWP, 2007).

Pollutant Removal Performance

Many of the research studies reviewed in this study have indicated that the performance and effectiveness of stormwater BMPs and LID practices can be measured in terms of pollutant removal or effluent quality, and/or in how well increased flows due to urbanization are reduced or mitigated. The monitoring methods used by industry experts to determine pollutant removal performance was analyzed. The International Stormwater BMP Database established by the American Society of Civil Engineers (ASCE) and United States Environmental Protection Agency (USEPA), and the National Pollutant Removal Performance Database managed by the Center for Watershed Protection (CWP) was the basis of this analysis.

Natural Processes Influencing Pollutant Removal

To understand pollutant removal performance, the natural processes that influence the performance of stormwater BMPs and LID practices must first be explained. The performance of stormwater treatment practices vary from site to site in relation to design specifications, local hydrologic and climatic conditions, and the age of the treatment practice. In addition, research on stormwater BMPs and LID practices is still relatively young, and the number of field experimental studies, like bioretention, is somewhat limited. The more information that is known about the functionality of stormwater treatment practices and the natural processes that take place within them, should ultimately lead to improved selection and stormwater designs that address local stormwater needs.

The primary pathways for removing pollutants from urban stormwater runoff are active within stormwater BMPs and LID practices. The primary pathways can be classified into three main categories – biological, chemical and physical processes (Figure 4-4). The main pollutant removal mechanisms found in stormwater treatment practices result in either the direct removal of a pollutant from the water column (e.g., sedimentation, adsorption to substrate, microbial degradation, filtration, phytoremediation, and volatilization), or the natural processes that indirectly contribute to the removal of a pollutant (e.g., precipitation, adsorption to suspended solids) (Scholes et al., 2008). Table 4-4 provides definitions, explanations and some examples of these processes.

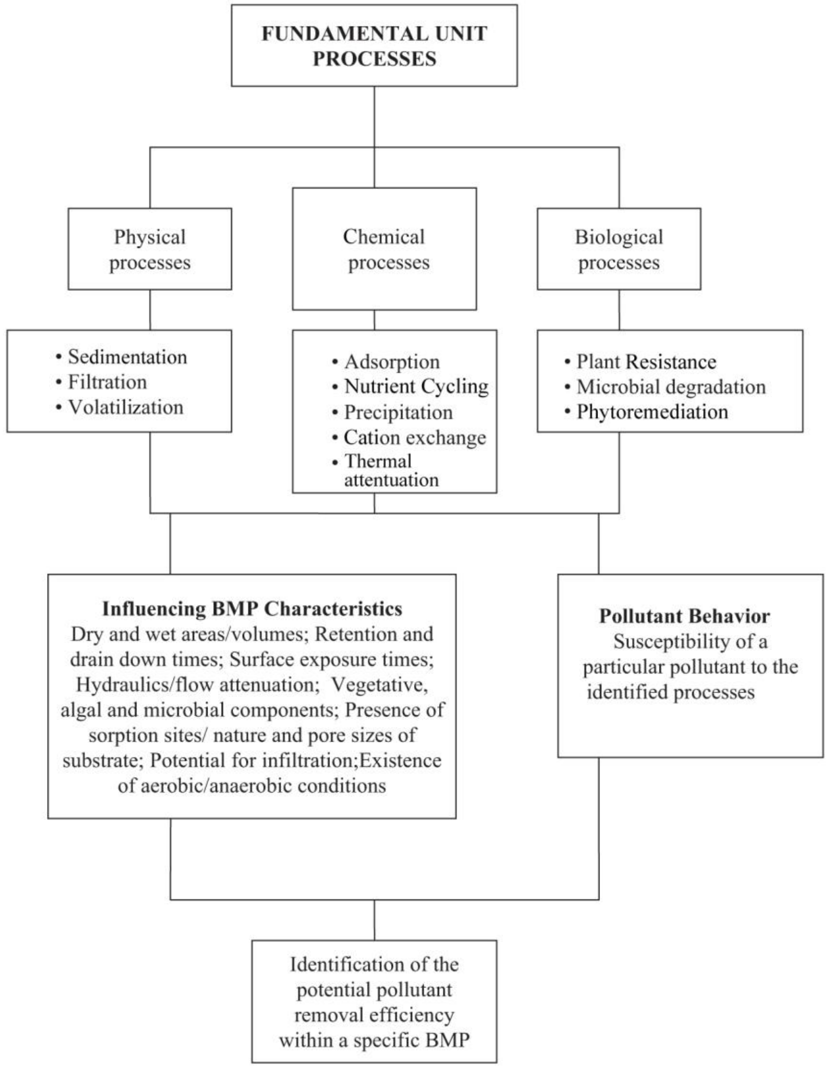


Figure 4-4: Fundamental Unit Processes in Relation to BMP Characteristics and Pollutant Behavior (adapted from Scholes et al., 2008)

Table 4-4: Definitions, Explanations and Examples of Physical, Chemical and Biological Processes (Sources: USEPA, 2000a; de la Crétaz and Barten, 2007; PGC, 2007; PSAT, 2007; Scholes et al., 2008)

Sedimentation is the settling of particulates and occurs in the pretreatment, if provided, and in the ponding area of the bioretention cell. Sedimentation is not effective for removing soluble components.
Filtration is the physical straining of particulates and is not an effective mechanism for removing soluble components. Some filtration occurs in the ponding area as the stormwater moves through plants, but the soil is the primary filtering media. Pitt et al. (1995) report that 90% of small particles commonly found in urban storm flows can be trapped by an 18" layer of sand. This level of performance can be anticipated for bioretention soils typically high in sand content.
Volatilization (or transpiration) occurs when a substance is converted to a more volatile vapor form. Denitrification and the transformation of complex hydrocarbons to carbon dioxide are examples of volatilization active in bioretention cells.
Adsorption is the binding of ions and molecules to electrostatic receptor sties on the filter media particles. This is the primary mechanism for removing soluble nutrients, metals and organics that occur in soil of bioretention areas as storm flows infiltrate. Adsorption increases with increased organic matter, clay and a neutral to slightly alkaline pH.
Nutrient Cycling is the cycle of biological and chemical elements and compounds in specific patterns through substances in an ecosystem – the uptake, use, release, and storage of nutrients by plants and their environments (phosphorus and nitrogen).
Cation Exchange is a chemical process in which cations of like charge are exchanged equally between a solid, such as soil, and a solution, such as water.
Thermal Attenuation reduces water temperatures as stormwater flows move through subsurface soil layers of a bioretention system. A field study in Maryland found that the temperature of the input water was reduced by approximately 12^{o}C after infiltrating through a bioretention cell located in a parking lot (USEPA, 2000b).
Plant Resistance occurs as plant materials reduce flow velocities and increase other pollutant removal pathways such as sedimentation, filtering and plant uptake of pollutants during growth periods.
Microbial Degradation occurs when microbial organisms transform or alter the structure of nutrients and organic materials that are introduced into the bioretention system. Aerobic and anaerobic processes are enhanced by the occurrence of high contact ratios between stormwater and substrate material.
Phytoremediation processes include degradation, uptake by the plant, containment within the plant (assimilation) or a combination of these mechanisms. Studies have shown that vegetated soils are capable of more effective degradation, removal and mineralization of total petroleum hydrocarbons, polycyclic aromatic hydrocarbons, pesticides, chlorinated solvents and surfactants than non-vegetated soils (USEPA, 2000a). Certain plant roots, like creeping juniper, can absorb or immobilize heavy metal pollutants (PSAT, 2005).

Bioretention systems use these natural processes to alter the properties of plants, microbes and soils to facilitate the removal of pollutants from urban stormwater runoff (Prince George's County, 2007). Nutrients are required for plant growth. Soils lacking in nutrients also affect plant growth. The use and overuse of fertilizers results in excess nutrients leaving a site either through groundwater transport or stormwater runoff. Excess nutrient pollution from phosphorus and nitrogen accelerates the eutrophication process which adversely affects downstream aquatic environments. Toxic algae blooms result from the excess of phosphorus and threaten many of the lakes and estuaries in the Northeast today (de la Crétaz and Barten, 2007). Additional water quality problems caused by excessive algae growth consist of decreased water clarity, habitat loss and fish kills (de la Crétaz and Barten, 2007; GC&WWE, 2010). For this reason, excessive nutrient loadings to receiving waterbodies must be managed. Additionally, the bioretention research studies previously analyzed have shown that retention of phosphorus and nitrogen has been problematic, therefore a deeper understanding of the natural processes that affect these two nutrients are examined more closely.

As shown in Figure 4-5, the natural cycle of phosphorus is an efficient process. Phosphorus is primarily transported by surface runoff and is adsorbed in compounds that contain iron, aluminum and calcium and tends to be held within the soil instead of being leached away (PGC, 2007). As a result, bioretention soil media that contain these metals can be very effective in the removal of this nutrient (GC&WWE, 2010). Some of the additional factors affecting removal of phosphorus consist of (GC&WWE, 2010):

- Particulate Association – particle size and density determine the time required for the particle to settle. The particle size distribution and densities of suspended solids in untreated stormwater are major factors affecting what may be removed from the treatment system. BMPs need to address both forms of phosphorus (dissolved and particulate) to achieve high/consistent pollutant removal rates.

- pH – phosphorus tends to precipitate onto particles at high pH. At higher pH, metals tend to precipitate onto particles, which create more sorption sites for phosphorus. Therefore, pH levels should be monitored annually to ensure low pH values are present for the release of phosphorus.

- P-Index – represents the amount of phosphorus already present in the soil and an important media/soil property in the adsorption process. Soils with a low P-index have been shown to improve phosphorus removal in bioretention cells and prevent leaching (Hunt et al., 2006).

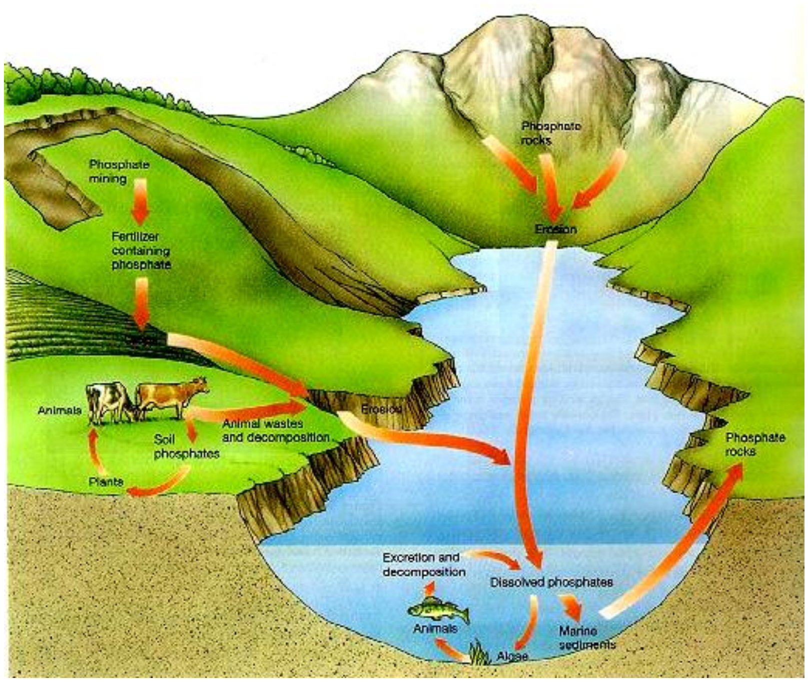


Figure 4-5: Phosphorus Cycle in Terrestrial and Aquatic Environments
(http://www.kirksville.k12.mo.us/khs/teacher_web/alternative/phosphorus-cycle.jpg, Accessed April 9, 2011)

The nitrogen cycle is a process by which nitrogen is converted between its multiple chemical forms through biological and non-biological processes (Figure 4-6). Nitrogen is present in stormwater runoff in one or more forms, depending on the source and the environmental conditions. Some of the common forms include organic nitrogen (dissolved or particulate), inorganic ions ammonium (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-). The important processes in the nitrogen cycle affecting pollutant removal performance are ammonification, nitrification, and denitrification (GC&WWE, 2010):

- Ammonification – when a plant dies, the initial form of nitrogen is organic. Bacteria convert the organic nitrogen within the remains of the plant back into ammonium. Ammonium is a suitable source of nutrition for many plant species, especially those species living in acidic soils. However, most plants cannot use ammonium effectively and require nitrate as their essential source of nitrogen nutrition.

- Nitrification – bacteria oxidize ammonia and ammonium ions to form nitrate (NO_3), a highly soluble form of nitrogen that is readily used by plants (PGC, 2007).

- Denitrification – when soil oxygen is low, temperatures are high and organic matter is plentiful, microorganisms reduce nitrate (NO_3) to volatile forms (such as nitrous oxide and nitrogen gas), which return to the atmosphere. One way to incorporate an anaerobic zone in a bioretention cell, use underdrain method described above; also mature soils with good structure denitrify more quickly.

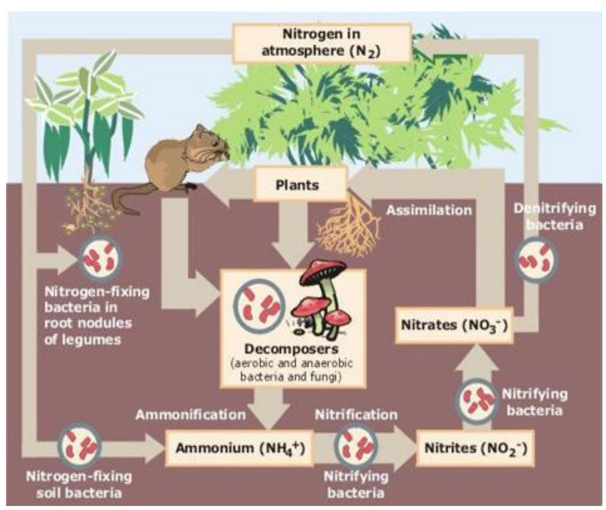


Figure 4-6: Nitrogen Cycle (http://www.epa.gov/caddis/images/nitrogen_cycle.png, Accessed April 9, 2011)

The removal of nitrogen can be influenced by several factors: temperature, pH, bacterial community and dissolved oxygen (GC&WWE, 2010). For instance, higher temperatures have yielded improvement in the ammonification, nitrification and denitrification processes; optimal rates of nitrogen removal occur when the soil pH is at or slightly higher than neutral; ammonification, nitrification and denitrification processes rely heavily on bacteria mediation, so the presence and abundance of specific bacteria communities affect the rate at which nitrogen is removed from these processes; and, in the case of dissolved oxygen, it must be present for nitrification to occur, and just the opposite for denitrification to occur, but only under anaerobic conditions (GC&WWE, 2010). The bioretention research studies previously discussed have shown that nitrogen removal is highly variable, but generally poor and at times, both production and export have been observed. For example, in a study by Hunt et al. (2006), the mass export of nutrients varied between two bioretention cells in North Carolina – one cell exhibited higher nitrogen reduction rates which may have resulted from microbial activity in an anaerobic zone, while the second cell had a high P-index in the bioretention soil media which potentially caused the phosphorus load to increase.

International Stormwater BMP Database

The International Stormwater BMP Database is a project that began in 1996 under a cooperative agreement between the American Society of Civil Engineers (ASCE) and the USEPA. The project is now supported by a number of partners – Water Environment Research Foundation (WERF), ASCE Environmental and Water Resources Institute (EWRI), Federal Highway Administration (FHWA) and the American Public Works Association (APWA). Wright Water Engineers, Inc. and Geosyntec Consultants are the entities that maintain and operate the database. One of the primary goals of the International Stormwater Best Management Practices (BMP) Database is to summarize data from existing field studies into a standardized format to analyze BMP performance. Once required protocols are met, these data are then entered into the BMP database via a BMP Data Entry Spreadsheet. Researchers are responsible for completing the data entry form for entry of their study to the database. As of 2010, the database contains over 400 BMP studies that can be searched online or downloaded from the website: http://www.bmpdatabase.org/. The BMP database is currently stored in Microsoft Access 2007 and is accessible to public agencies, consultants, university professors and researchers, and graduate students. The database includes multiple lookup tables that can be linked together by key fields, such as test site, watershed, BMP, event and monitoring station. Figure 4-7 provides a detailed overview of the general relationships between various types of requested data.

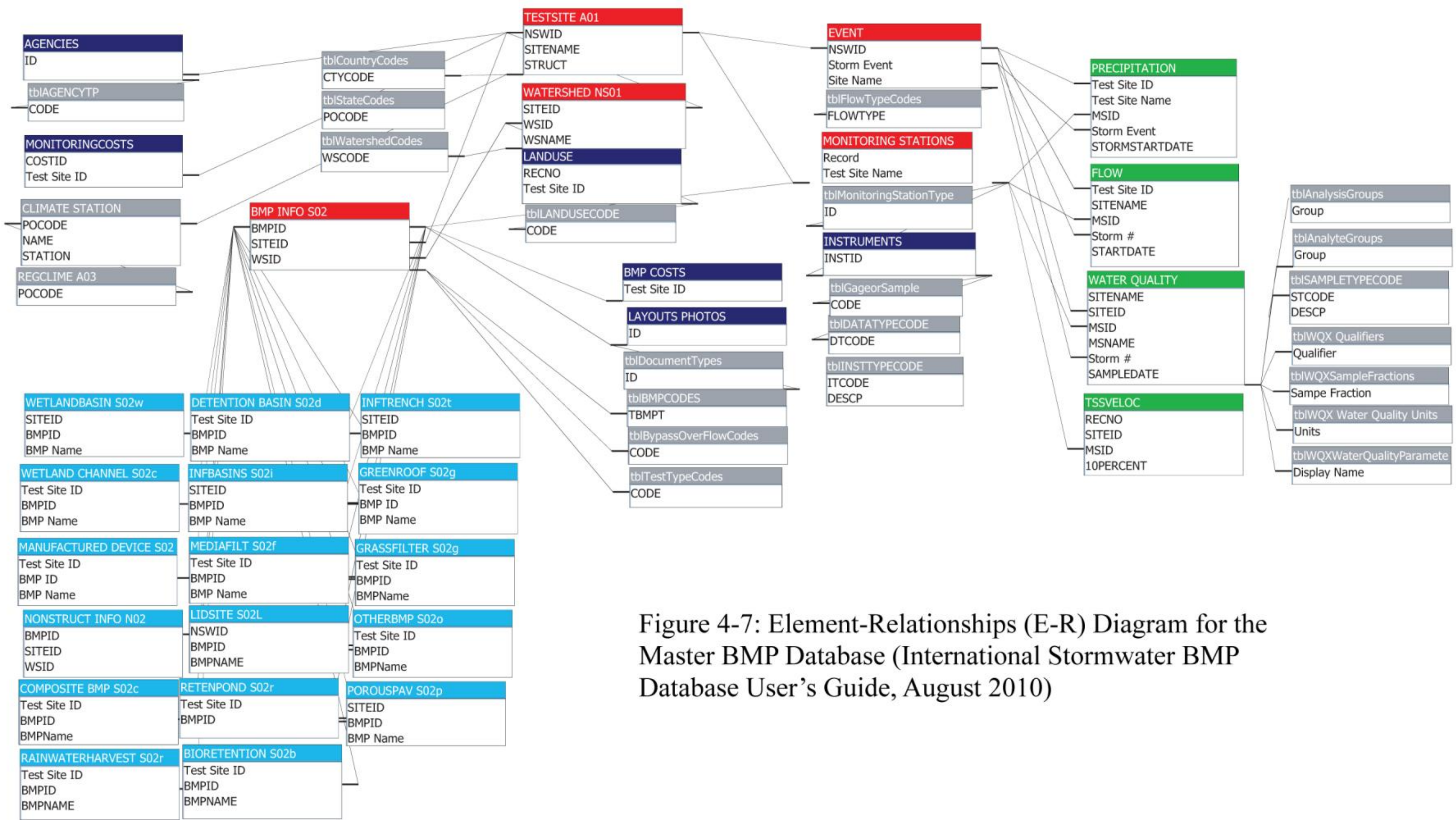


Figure 4-7: Element-Relationships (E-R) Diagram for the Master BMP Database (International Stormwater BMP Database User's Guide, August 2010)

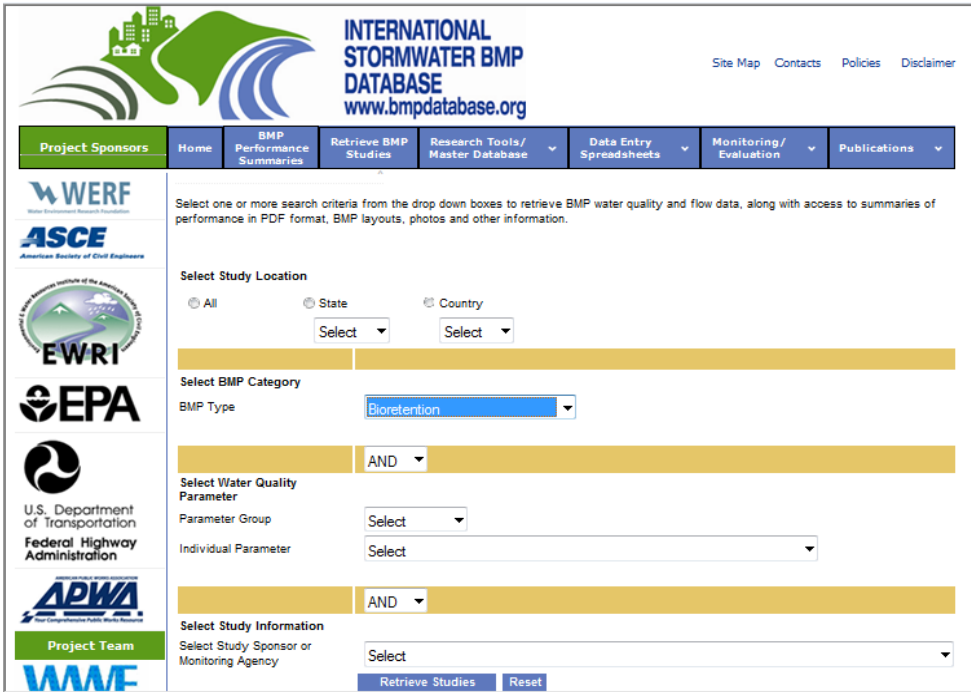


Figure 4-8: Screen Print of the BMP Study Retrieval Function in the International Stormwater BMP Database (http://www.bmpdatabase.org/retrieveBMPs.asp, Accessed March 28, 2011)

Through a separate function on the website, individual BMP studies can also be retrieved for statistical analysis based on BMP category and selected water quality parameters (Figure 4-8). The BMP study retrieval function was used to conduct a search to determine the number of bioretention studies that have been entered into the database for analysis of pollutant removal performance. The search revealed twelve bioretention studies located in nine geographic regions of the United States, mostly in the east (Figure 4-9):

- Durham, NH
- Villanova, PA
- Newark, DE
- Charlottesville, VA
- Graham, NC
- Greensboro, NC
- Charlotte, NC
- Louisburg, NC
- Auburn, WA

Figure 4-9: Geographic Location of Bioretention Studies in the United States (International Stormwater BMP Database)

For each BMP study retrieved, reports are provided that contain specific information relating to the description of the BMP study, precipitation data, water quality data by constituent based on the EMC method of calculation, and flow data, which was limited for most of the bioretention studies reviewed. Table 4-5 contains summary information for the twelve bioretention studies. Most of the installations were in late 1990 to early 2000. All studies varied in size, total watershed area and the amount of impervious surface cover. Most of these categories would be key in conducting comparisons between studies. Interesting to note that data pertaining to surface infiltration rate, media depth and ponding volume are sparsely complete, making comparisons between studies somewhat difficult for those categories.

Table 4-5: Summary Information of the Bioretention Studies in the International Stormwater BMP Database

Bioretention Test Site	Install Date	Sponsoring/ Monitoring Agency	Test Site	Surface Area	Surface Infiltration Rate	Media Type	Media Depth	Underdrains	Ponding Volume	Pretreatment	Total Watershed Area	% Impervious	Primary Land Use
Durham, NH	9/1/2004	Cooperative Institute for Coastal & Estuarine Env. Tech.	Bio Cell	-	-	Amended	-	1	-	Yes	0.4 ha	100	College Campus: 100%
Villanova, PA	8/1/2001	PA Growing Greener and USEPA	Traffic Island	$139.5m^2$	0.635cm/hr	Amended	-	0	$34.54674m^3$	-	0.49 ha	41%	Open Space: 60% Auto Svcs: 40%
Newark, DE	8/1/2004	Delaware Dept. of Transportation	Interstate Plaza	-	-	-	-	1	-	-	0.8 ha	80%	Roads/ Highways: 100%
Charlottesville, VA	6/2/1998	VA Dept of Conservation & Recreation	Municipal Parking Lot	$229m^2$	-	Amended	-	2	-	-	0.32 ha	100	Institutional: 100%
Graham, NC (north cell)	6/1/2005	North Carolina State University	High School Parking Lot	$102.2m^2$	-	Amended	-	1	-	Yes	7.16 ha	33%	Medium Density Residential: 100%
Graham, NC (south cell)	6/1/2005	North Carolina State University	High School Parking Lot	$102.2m^2$	-	Amended	-	1	-	Yes	7.16 ha	33%	Medium Density Residential: 100%
Greensboro, NC (cell 1)	2001	North Carolina State University	Bio Cell	$100m^2$	15in/hr	Amended	1.2m	2	23,000L	Yes	0.2 ha	100%	Retail: 100%
Greensboro, NC (cell 2)	2001	North Carolina State University	Bio Cell	$100m^2$	15in/hr	Amended	1.2m	2	23,000L	Yes	0.19 ha	100%	Retail: 100%
Charlotte, NC	12/1/2003	City of Charlotte, NC	Bio Cell	$229m^2$	-	Amended	1.2m	1	$41m^3$	No	0.37 ha	100%	Office Commercial: 100%
Louisburg, NC (cell 1)	2004	North Carolina State University	Bio Cell	$162m^2$	-	Amended	0.6m	2	24,300L	Yes	0.36 ha	95%	Open Space: 95%
Louisburg, NC (cell 2)	2004	North Carolina State University	Bio Cell	$99m^2$	-	Amended	0.6m	2	14,850L	Yes	0.22 ha	45%	Open Space: 45%
Auburn, WA	12/28/1997	WA State Dept of Transportation	Ecology Embankment	-	-	-	-	1	-	-	0.2 ha	100%	Roads/ Highways: 100%

An analysis of the precipitation data can be found in Table 4-6 which shows the regional climate data averaged over a 30-year period and site specific precipitation for each of the nine geographic locations. Eight out the 12 studies collected precipitation data for 25-35 storm events for their respective monitoring periods. In most cases, the average depth of precipitation was approximately 1 inch per storm event. Precipitation data is important to understand the hydrologic and hydraulic parameters of a stormwater monitoring program, as well as whether the stormwater treatment practice is meeting its goal in capturing the total runoff volume to mimic pre-development hydrology. Precipitation data is also a key determinate when evaluating the sizing of bioretention systems to accommodate a specified design storm volume.

Table 4-6: Precipitation Data for the Bioretention Studies in the International Stormwater BMP Database

Bioretention Test Site	Climate Station Location	Regional Climate Data: Mean Annual Number of Storms	Mean Annual Precipitation Total (cm)	Mean Storm Duration (hrs)	Mean Storm Intensity (cm/hr)	Mean Period Between Storms (hrs)	Site-Specific Precipitation: Number of Events Monitored	Period of Study	Average Depth of Precipitation (cm)
Durham, NC	Concord	62	35.17	12	0.061	143	24	9/2004 - 5/2006	2.34
Villanova, PA	Philadelphia	62	39.68	10.3	0.85	144	290	1/2003 - 10/2008	2.44
Newark, DE	N/A	-	-	-	-	-	10	4/2005 - 11/2007	1.41
Charlottesville, VA	Lynchburg	62	38.26	10.9	0.85	142	32	11/1998 - 11/1999	1.45
Graham, NC (north cell)	Raleigh Durham	62	40.12	9.6	0.099	144	26	4/2006 - 4/2007	2.37
Graham, NC (south cell)	Raleigh Durham	62	40.12	9.6	0.099	144	26	4/2006 - 4/2007	2.37
Greensboro, NC (cell 1)	N/A	-	-	-	-	-	57	7/2003 - 9/2004	2.63
Greensboro, NC (cell 2)	N/A	-	-	-	-	-	65	7/2003 - 9/2004	2.3
Charlotte, NC	Charlotte	63	40.79	9.5	0.098	141	30	2/2004 - 3/2006	2.47
Louisburg, NC (cell 1)	N/A	-	-	-	-	-	30	5/2004 - 12/2004	2.4
Louisburg, NC (cell 2)	N/A	-	-	-	-	-	30	5/2004 - 12/2004	2.4
Auburn, WA	Seattle	71	34.31	14.6	0.036	121	25	8/2001 - 2/2005	1.22

Table 4-7 presents an analysis of the water quality data by constituent based on the EMC method of calculation. The available data set for the bioretention studies consisted of many constituents, however, only pollutant removal performance was evaluated for total suspended solids (TSS), total phosphorus (TP), nitrogen (NO_2 + NO_3) as N, total Kjeldahl nitrogen (TKN), total zinc and total chloride. The rest were excluded from the analysis because pollutant removal performance was based on less than two studies. Although flow data was available for most of the studies, this data is not presented as part of this analysis. TSS, nitrogen (NO_2 + NO_3) as N, and total zinc showed substantial decreases in reduction concentrations. Compared to inflow concentrations, TP, TKN and total chloride showed increased concentrations in the outflow for their monitoring periods. Decreases in pollutant removal performance could be for any number of reasons, but it is difficult to ascertain without a standard protocol in place to pursue this information further. In reviewing information stored in the International Stormwater BMP Database, wide variations are observed in the outflow concentrations for different studies of the same BMP type, i.e., bioretention. This performance most likely varies because of location, design, application of design, rainfall patterns, surrounding land uses, monitoring variability and many other factors. Nonetheless, nutrient data can be useful for characterizing classes of BMP treatment performance on a statistical basis. However, determining the reliability of this method for basing decisions on design improvements is unclear, especially when flow data is not considered part of this statistical analysis process.

Table 4-7: Bioretention Influent & Effluent Summary Statistics in the International Stormwater BMP Database

Constituent	Number of Studies	Mean (mg/L)		25th Percentile (mg/L)		Median (mg/L)		75th Percentile (mg/L)		Comparison
		In	Out	In	Out	In	Out	In	Out	
Total Suspended Solids	6	96.13	37.17	28.56	11.10	58.69	24.00	114.39	50.98	Decrease
Total Phosphorus	12	0.26	0.63	0.12	0.29	0.20	0.36	0.33	1.45	Increase
Nitrogen, NO2 + NO3 as N	10	0.44	0.39	0.21	0.18	0.33	0.31	0.51	0.43	Decrease
Total Kjeldahl Nitrogen	8	1.51	2.06	0.78	1.42	1.16	1.82	1.63	2.31	Increase
Total Zinc	4	130.47	31.98	78.31	18.24	114.38	24.75	180.13	35.57	Decrease
Total Chloride	3	205.10	338.27	39.95	85.96	69.22	145.71	114.54	348.34	Increase

National Pollutant Removal Performance Database

The National Pollutant Removal Performance Database was first introduced in 1997 by Whitney Brown and Tom Schueler to present results of BMP monitoring studies and pollutant removal performance data for stormwater treatment practices (Winer, 2000). The database is managed by the Center for Watershed Protection (CWP) and is intended to be used by engineers, planners and municipal agencies who are interested in watershed restoration and protection, and stormwater management strategies and design. Database results are accessible through publication of reports by the CWP that are periodically updated when BMP performance monitoring studies are completed and the corresponding results are published. Since its inception, the database now includes over 150 individual BMP performance studies published through 2006 (Table 4-8) (CWP, 2007). For inclusion into the database, all BMP studies must meet three target criteria: (1) five or more samples were collected; (2) automated equipment was used to collect flow- or time-based composite samples; and, (3) the method used to compute removal efficiency was documented (CWP, 2007). The last element is an important one because it determines whether or not the data is entered into the database.

The pollutant removal efficiencies entered into the National Pollutant Removal Performance Database and computed in plots and tables are based on mass or load-based measurements (CWP, 2007), rather than on concentrations. As discussed previously, EMC efficiency based on concentration calculates the average of the inflow and outflow concentrations for all storms and does not account for water volume. This method generally reports lower performance metrics. On the other hand, the Summation of Loads method used by this database calculates mass efficiency based on the sum of incoming and outgoing loads and is considered to be a more accurate indicator of removal performance (CWP, 2007). Although total flow volume is part of the equation, volume reduction is not reported in the database.

Table 4-8: Number of Studies by BMP Category included in the National Pollutant Removal Performance Database (CWP, 2007)

Practice	Number of Studies
Dry Ponds	**10**
Quality Control Pond	3
Dry ED Pond	7
Wet Ponds	**46**
Wet ED Pond	15
Multiple Pond	1
Wet Pond	30
Wetlands	**40**
Shallow Marsh	24
ED Wetland	4
Pond/Wetland System	10
Submerged Gravel Wetland	2
Filtering	**18**
Organic Filter	7
Sand Filter	11
Bioretention	**10**
Infiltration	**12**
Infiltration Trench	3
Porous Pavement	9
Open Channels	**17**
Grass Channel	3
Dry Swale	12
Wet Swale	2
Total	**153**

In the latest published report of the National Pollutant Removal Performance Database report (CWP, 2007), ten bioretention studies have been added since the last update in 2002 (Table 4-8). For each BMP category in the database, the mass removal efficiency is reported graphically as a “Box and Whisker” plot that corresponds to a table charted by pollutant. The data is then statistically analyzed to derive median and quartile removal values for each group of stormwater BMPs. Figure 4-10 and Table 4-9 display the results of the ten bioretention studies included in the database. When selecting and designing BMPs for stormwater control, the Center for Watershed Protection (CWP) recommends using the Q3/75th percentile removal efficiency numbers as the design objective to achieve the best possible performance in lieu of the median value (CWP, 2007). The Q3/75th percentile removal efficiency for bioretention is highlighted in Table 4-9. Although there is a strong tendency to use median values when developing stormwater programs, the decision to use median values can lead to design standards that aim towards the middle range of performance, and thus, inadequate stormwater controls on the ground (CWP, 2007).

Table 4-9 presents the cumulative pollutant removal performance of all ten bioretention studies. The table also identifies the constituents monitored by the number of bioretention studies. For example, all ten studies monitored total phosphorus and eight monitored total nitrogen, which identifies that phosphorus and nitrogen reduction as the two most important pollutants being studied by the research. While the pollutant removal performance results show reductions for most constituents monitored, phosphorus is showing that production and export may be occurring in all ten bioretention systems. Unfortunately, it is difficult to understand why because the context in which to review the data is not readily available, as well as volume reduction results. In addition, bacteria removal data is listed as “N/A” with no further explanation.

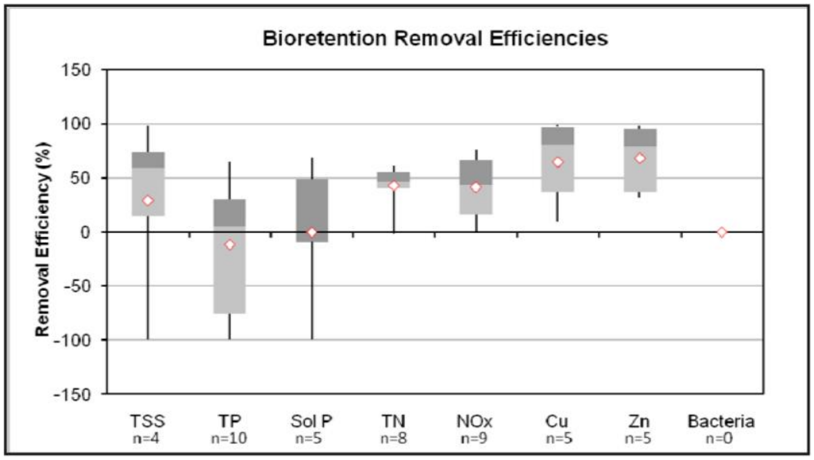


Figure 4-10: Bioretention Removal Efficiencies (CWP, 2007)

Note: Summary description to interpret plot and table information:

- Median Efficiency = where light and dark gray bars meet
- Average Efficiency = small diamond
- Q1/25th Percentile = bottom of light gray bar
- Q3/75th Percentile = top of dark gray bar
- Maximum/Highest Value = top of line
- Minimum/Lowest Value = bottom of line
- Number of studies analyzed for each pollutant = n

Table 4-9: Bioretention Mass Removal Efficiency Statistics (CWP, 2007)

	Total Suspended Solids	Total Phosphorus	Soluble Phosphorus	Total Nitrogen	Nitrogen as Nitrate & Nitrite	Copper	Zinc	Bacteria*
Median	59	5	-9	46	43	81	79	N/A
Minimum	-100	-100	-100	-2	0	9	31	N/A
Maximum	98	65	69	61	76	99	98	N/A
Q1/25th Percentile	15	-76	-9	40	16	37	37	N/A
Q3/75th Percentile	74	30	49	55	67	97	95	N/A
Number	4	10	5	8	9	5	5	0

The International Stormwater BMP Database and the National Pollutant Removal Performance Database document the performance results of research studies being conducting throughout the United States. The two sources of information provide pollutant removal performance results across various stormwater BMP and LID practices. Both databases use different methods to calculate and report the results, but nevertheless, they are results. Poor results for phosphorus and nitrogen removals in bioretention systems were consistent between the two databases, but with no explanation or method provided to understand why or how to look more specifically at the details to find out why. This information is absent from both databases and could be the critical link that connects performance with design standards changes that ultimately improve stormwater treatment practices.

LID Monitoring Case Studies

Low Impact Development (LID) is a stormwater strategy that can be used to reduce runoff and pollutant loadings by managing urban runoff close to the source. This section of the chapter presents and examines two case studies of LID monitoring projects – the Jordan Cove Watershed Project in Watertown, CT and the field research site at the University of New Hampshire Stormwater Center (UNHSC) in Durham, NH with specific emphasis on bioretention – to provide insights into methods potentially applicable to future monitoring projects in New England urban environments, as well as implications to design standards. These case studies were chosen because of their relationship to New England and because the projects cover a range of LID practices. Table 4-10 summarizes the major monitoring design components of each study.

Table 4-10: Case Studies Summary

					Type of Constituent Tested		
Case Study	Number of Rain Gauges	Number of Flow Locations	Automated Samplers Used?	Grab Samples?	Nutrients	Metals	Other
Jordan Cove, Watertown, CT							
Control	-	1	Yes	Yes	Yes	Yes	Yes
Traditional Stormwater Design	-	1	Yes	Yes	Yes	Yes	Yes
LID Treatment Practices	1	1	Yes	Yes	Yes	Yes	Yes
UNHSC, Durham, NH							
Bioretention System	1	2	Yes	No	Yes	Yes	Yes

Jordan Cove Watershed Project

In the early 1990s, water quality sampling in Long Island Sound revealed that this waterbody was not meeting water quality standards due to NPS pollution (Clausen, 2007). A study was conducted by the New York State Department of Environmental Conservation (NYSDEC) and the Connecticut Department of Environmental Protection (CTDEP) to research, monitor and assess the water quality of Long Island Sound. As a result, a comprehensive plan was developed to focus on several key areas to be addressed in protecting and improving the environmental quality of the Sound: low dissolved oxygen/hypoxia; toxic contamination; pathogen contamination; floatable debris; the impact of these water quality problems, and habitat degradation and loss, on the health of living resources; land use and development resulting in habitat loss and degradation of water quality; and, public involvement and education. Results of the study concluded that a substantial portion of the Sound was being affecting by hypoxia from high nitrogen loads during the summer months (NYSDEC and CTDEP, 2000). Consequently, the USEPA approved and specified a TMDL for Long Island Sound of 58.5% reduction in nitrogen loads (human generated) from point and NPS sources over a 15-year period with full implementation by 2014 (CTDEP, 2005).

Jordan Cove is a small estuary composed of a 1.75-mile long narrow neck that feeds into an inner and outer cove before flowing into Long Island Sound (Figure 4-11). The Jordan Cove Watershed Monitoring Project was funded largely in part by a nonpoint source (NPS) grant under Section 319 of the Clean Water Act by the USEPA and Connecticut Environmental Protection Agency. This 10-year monitoring project studied the effects of residential subdivision development on runoff quality and quantity using a paired watershed approach, and was the first of its kind to study the application of LID practices designed at the site level to mitigate the effects of urbanization and NPS pollution. Three catchments were monitored and compared: (1) a control catchment (Figure 4-12), which was not altered at any time during the monitoring period; (2) a traditional catchment (Figure 4-13), which used traditional conveyance methods (e.g., curbs, gutters and sewers) for stormwater control and was constructed during the monitoring period; and, (3) a LID catchment (Figure 4-13) that implemented LID practices throughout this portion of the development, such as bioswales, bioretention cells, permeable paving, shared driveways, open areas and clustered housing, and was also constructed during the monitoring period. Specific characteristics of each catchment are noted in Table 4-11. Examples of LID practices installed on the LID Subdivision Watershed site are shown in Figures 4-14 and 4-15.

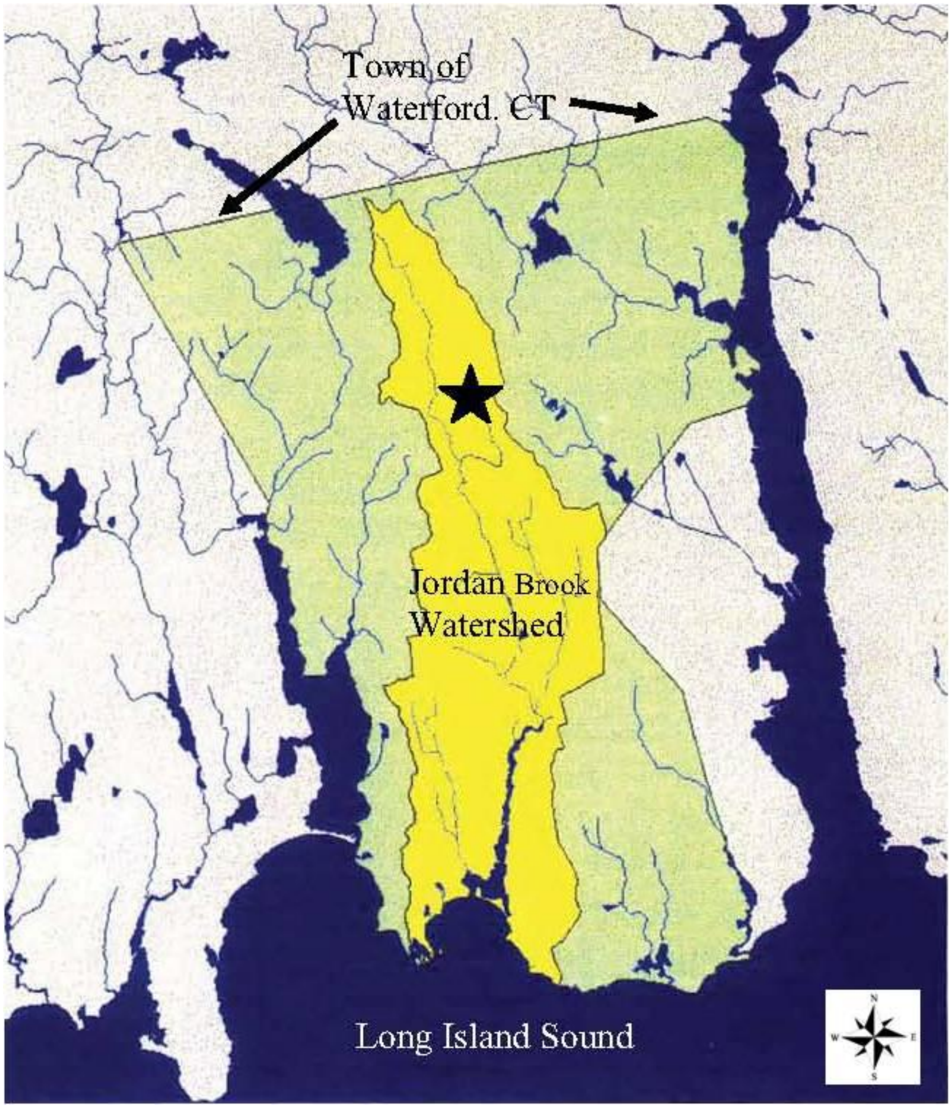


Figure 4-11: Jordan Cove Watershed Showing Location of Project (Clausen, 2007)
(no scale provided)

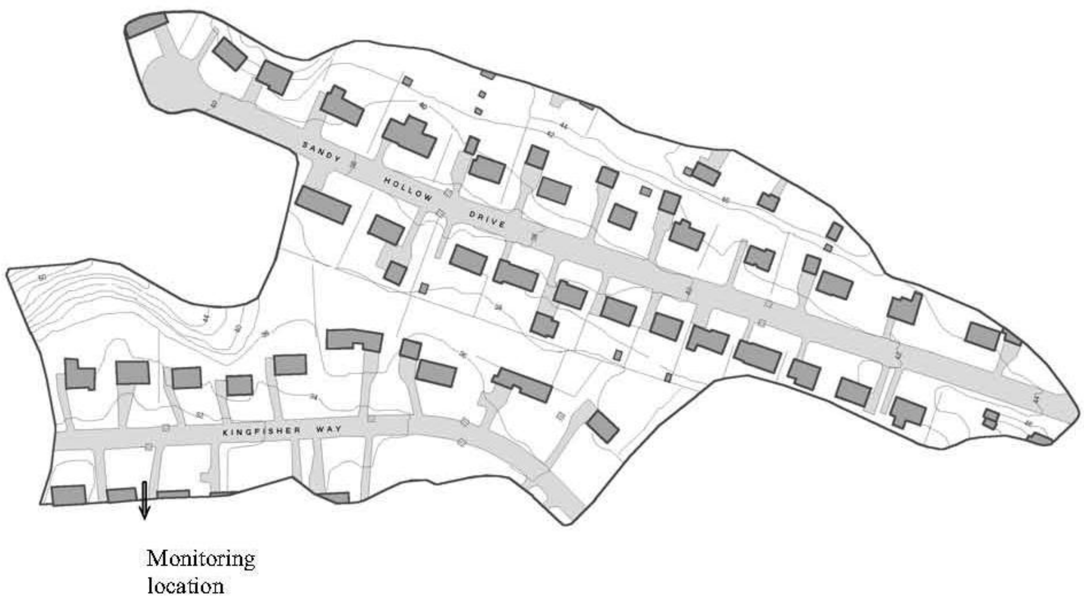


Figure 4-12: Control Watershed Subdivision (Clausen, 2007)

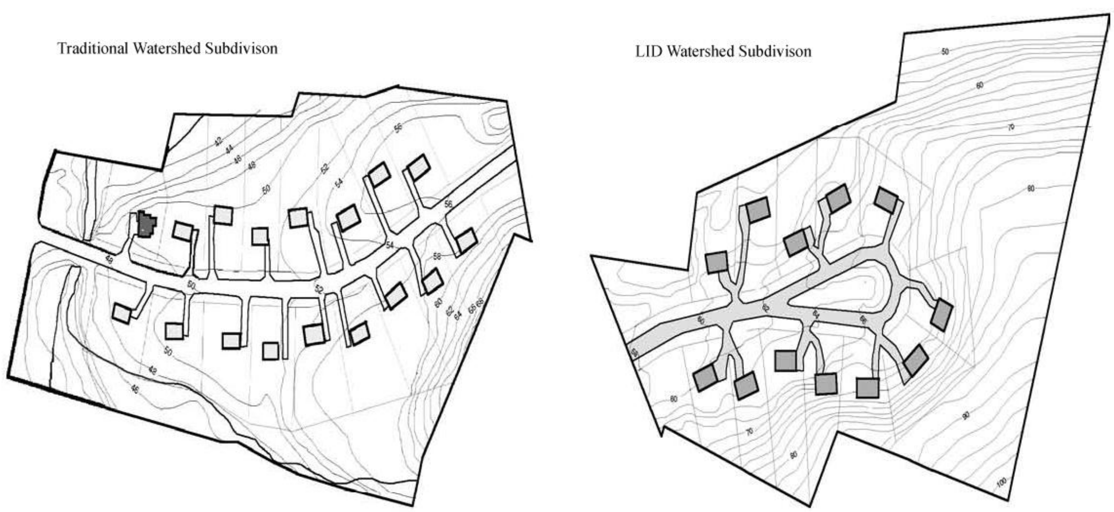


Figure 4-13: Traditional and LID Watershed Subdivisions (Clausen, 2007)

Table 4-11: Characteristics of Study Watersheds (Clausen, 2007; Bedan and Clausen, 2009)

Characteristic	Control	Traditional	LID
Watershed Area (ha)	5.5	2.0	1.7
Number of Lots	43	17	12
Average Lot Size (ha)	0.16	0.15	0.10
% Total Impervious	29	32	22
Average Slope (%)	1.0	1.5	1.8

Figure 4-14: (Left) Grassed Bioswale along Side of Street (in place of curb and gutters) in the Jordan Cove LID Development (Clausen, 2007)
Figure 4-15: (Right) Pervious Concrete-Paver Road (in place of traditional asphalt) in the Jordan Cove LID Development (Clausen, 2007)

The monitoring schedule occurred over a ten-year period (Table 4-12) and included the calibration period prior to the start of construction, and the construction and post-construction periods of the traditional and LID catchment developments. No land use changes occurred during the calibration period and regression relationships of paired runoff observations were established between the control and two treatment watersheds (Bedan and Clausen, 2009). This phased approach facilitated the study of the changing effects on water quality and runoff quantity throughout the entire development process.

Table 4-12: Jordan Cove Monitoring Schedule (Bedan and Clausen, 2009)

Watershed	Calibration Period	Construction Period	Post-Construction Period
Control	11/1/1995	to	6/30/2005
Traditional	4/4/1996 to 10/8/1997	10/8/1997 to 6/19/2003	6/19/2003 to 6/30/2005
LID	1/18/1996 to 3/23/1999	3/23/1999 to 8/1/2002	8/1/2002 to 6/30/2005

Precipitation was recorded at the LID development site and air temperature was also continuously monitored to allow for the distinction between snowmelt periods and precipitation events. The monitoring program consisted of measuring the flow rates of the stormwater runoff from the three watersheds, and collecting weekly flow-weighted, composite samples for every 500ft^3 of discharge using automated samplers positioned at the outlet of each catchment (Clausen, 2007; Bedan and Clausen, 2009). The water quality parameters monitored were total suspended solids (TSS), total phosphorus (TP), total Kjeldahl nitrogen (TKN), ammonia-nitrogen (NH_3-N), nitrate+nitrite-nitrogen (NO_3+NO_2-N), copper, zinc and lead. Grab samples were also collected for any discharge that occurred during site visits for analysis of fecal coliform and 5-day biochemical oxygen demand (BOD_5). All data were statistically analyzed using: (1) analysis of variance (ANOVA) to test the significance of the regressions in each period; and, (2) analysis of covariance (ANCOVA) to test the differences between the two regression slopes and intercepts (Clausen, 2007; Bedan and Clausen, 2009). Most water quality data were log-normally distributed to present means that were anti-logs of log-transformed data, and the percent change in flow, concentrations and mass exports were calculated by comparing the mean predicted values from the calibration regression equations to observed values using the equation: % change = [(Observed – Predicted)/Predicted]*100 (Clausen, 2007; Bedan and Clausen, 2009).

The climate affecting the Jordan Cove Watershed Monitoring Project was influenced by continental polar and maritime tropical air masses, and the overall precipitation during this study averaged 5% below the average annual precipitation of 123.75cm (Clausen, 2007; Bedan and Clausen, 2009). Target goals were established for the LID development to assess the performance of the stormwater treatment practices and whether the goals were achieved (Table 4-13).

Table 4-13: Treatment Goals of Jordan Cove LID Watershed (Clausen, 2007)

Number	Treatment Goal	Outcome
1	Implement LID practices on 100% of the lots in the LID development.	Goal met
2	Maintain post-development peak runoff rate and volume at levels equal to pre-development rates.	Goal met
3	Maintain post-development loading of TSS at levels equal to pre-development rates.	Goal not met
4	Retain sediment onsite during construction.	Goal not met
5	Reduce nitrogen export by 65%.	Goal met
6	Reduce bacterial export by 85%.	Goal not met
7	Reduce phosphorus export by 40%.	Goal met

Table 4-14 and 4-15 present the results of the LID and traditional watersheds in comparison to the control watershed for water quantity and water quality performance. Pre-development peak runoff rates and stormflow volumes in the LID watershed were maintained during the postconstruction period for the events monitored, while significant increases were observed in the traditional watershed likely due to the use of conveyance stormwater controls and impervious surfaces. The increased storm flow observed in the traditional development (Table 4-14) directly contributed to substantial increases in subsequent pollutant loadings for nitrogen, phosphorus, total suspended solids, copper and zinc. The impact of urbanization in the traditional development is clearly shown in the study results – increases in stormwater runoff resulted in increases in pollutant loads.

As shown in Table 4-15, the volume of runoff was reduced in response to implementing LID practices in the LID watershed, however, the mass export of the constituents monitored produced varied results. For example, nitrogen (NH_3-N and TKN), lead and zinc loads were reduced significantly due to the decrease in stormflow (Clausen, 2007; Bedan and Clausen, 2009). On the other hand, concentrations and mass export of phosphorus increased significantly in the postconstruction period likely due to fertilization and leaching from autumn leaves. Additionally, post-development total suspended solids levels were also greater than pre-development levels due to stormwater being directed through the grassed swales in the LID development (Clausen, 2007; Bedan and Clausen, 2009).

Table 4-14: Mean Predicted and Observed Values and Percent Change from the LID and Control Watersheds during the Calibration and Postconstruction Periods (Bedan and Clausen, 2009)

	Calibration Period (n = 90)[1]		Postconstruction Period (n = 75)[2]					ANCOVA	
				LID					
Characteristic	Control	LID	Control	Observed	Predicted	Calibration Equation	% Change	F	p
Storm flow (cm/week)	0.21	0.17	0.40	0.13	0.22	$T = 0.407C^{0.674}$	−42***	17.77	<0.001
Peak discharge (m^3/s/week)	0.0360	0.0057	0.0262	0.0030	0.0041	$T = 0.147C^{0.279}$	−26$^{N.S.}$	5.91	0.001
NO_3-N (mg/l)	0.5	0.2	1.3	0.4	0.2	$T = 0.201C^{-0.106}$	+100*	3.33	0.021
NH_3-N (mg/l)	0.20	0.05	0.14	0.03	0.06	$T = 0.089C^{0.193}$	−50*	8.61	<0.001
TKN (mg/l)	1.3	0.9	1.2	1.3	0.9	$T = 0.816C^{0.343}$	+44**	20.37	<0.001
TP (mg/l)	0.139	0.027	0.165	0.291	0.028	$T = 0.052C^{0.349}$	+939***	50.71	<0.001
TSS (mg/l)	29	4	24	11	4	$T = 1.862C^{0.22}$	+197***	10.60	<0.001
BOD_5 (mg/l)	2.9	2.9	3.1	3.3	3.4	$T = 1.535C^{0.705}$	−3$^{N.S.}$	9.72	<0.001
Fecal coliform (No/100 ml)	10	62	305	41	790	$T = 17.091C^{0.67}$	−95**	5.57	0.006
Cu (μg/l)	10	8	10	6	8	$T = 6.116C^{0.12}$	−25$^{N.S.}$	0.96	0.419
Pb (μg/l)	6	4	2	1	3	$T = 2.674C^{0.157}$	−67***	10.05	<0.001
Zn (μg/l)	69	88	40	17	74	$T = 18.146C^{0.38}$	−77***	9.63	<0.001
NO_3-N (kg/ha/year)	0.55	0.18	4.02	0.25	0.34	$T = 1.99C^{0.271}$	−26$^{N.S.}$	5.49	0.001
NH_3-N (kg/ha/year)	0.23	0.05	0.43	0.02	0.08	$T = 1.034C^{0.183}$	−71***	9.26	<0.001
TKN (kg/ha/year)	1.59	0.73	3.99	0.90	1.36	$T = 2.006C^{0.592}$	−33*	16.67	<0.001
TP (kg/ha/year)	0.17	0.04	0.52	0.21	0.06	$T = 0.404C^{0.454}$	+249**	23.83	<0.001
TSS (kg/ha/year)	35	3	75	8	5	$T = 4.96C^{0.394}$	+85*	20.28	<0.001
Cu (g/ha/year)	13	6	21	4	7	$T = 10.862C^{0.535}$	−50$^{N.S.}$	2.03	0.122
Pb (g/ha/year)	7	3	5	0.5	2	$T = 46.016C^{0.234}$	−79**	5.41	0.003
Zn (g/ha/year)	85	65	87	10	56	$T = 0.435C^{1.044}$	−81**	7.65	<0.001
Fecal coliform (No/ha/year × 10^6)	56	1,893	2,713	39	521	$T = 6,061,917C^{0.125}$	−99**	3.78	0.032

Notes: C = control; N.S. = not significant; T = treatment.
[1]n = number of samples; n for FC and metals were 20 and 28, respectively.
[2]n for FC and metals were 7 and 20, respectively.
*p < 0.05.
**p < 0.01.
***p < 0.001.

Table 4-15: Mean Predicted and Observed Values and Percent Change from the Traditional and Control Watersheds during the Calibration and Postconstruction Periods (Bedan and Clausen, 2009)

Characteristic	Calibration Period (n = 10)[1] Control	Calibration Period (n = 10)[1] Traditional	Postconstruction Period (n = 56)[2] Control	Postconstruction Period (n = 56)[2] Traditional Observed	Postconstruction Period (n = 56)[2] Traditional Predicted	Calibration Equation	% Change	ANCOVA F	ANCOVA p
Storm flow (cm/week)	0.20	0.02	0.35	0.33	0.02	$T = 0.028C^{0.285}$	+1,550***	27.78	<0.001
Peak discharge (m^3/s/week)	0.0525	0.0005	0.0246	0.0152	0.0005	$T = 0.018C^{-0.073}$	+2,829***	63.58	<0.001
NO_3N (mg/l)	0.5	0.3	1.1	0.3	0.3	$T = 0.340C^{0.084}$	0	0.50	0.626
NH_3-N (mg/l)	0.15	0.08	0.16	0.15	0.13	$T = 0.313C^{0.498}$	$+15^{N.S.}$	4.00	0.012
TKN (mg/l)	1.3	4.0	1.1	1.0	4.1	$T = 3.999C^{0.196}$	−76***	20.68	<0.001
TP (mg/l)	0.159	1.009	0.156	0.185	0.885	$T = 3.494C^{0.739}$	−79***	10.99	<0.001
TSS (mg/l)	31	132	22	24	114	$T = 53.239C^{0.247}$	−79*	10.18	<0.001
BOD (mg/l)	3.2	15.9	3.2	3.4	11.8	$T = 18.0C^{-0.363}$	−71**	10.78	0.008
Fecal coliform (No/100 ml)	13	1	234	22	<1	$T = 0.654C^{-0.698}$	undefined	1.60	0.300
Cu (μg/l)	7	8	9	7	10	$T = 3.163C^{0.533}$	$-30^{N.S.}$	2.64	0.074
Pb (μg/l)	6	11	1	1	1	$T = 0.762C^{1.478}$	0	11.39	<0.001
Zn (μg/l)	46	65	36	42	67	$T = 11.414C^{0.492}$	$-37^{N.S.}$	1.86	0.164
NO_3-N (kg/ha/year)	0.61	0.01	3.29	0.83	0.04	$T = 0.008C^{1.081}$	+2,181***	38.77	<0.001
NH_3-N (kg/ha/year)	0.17	0.01	0.48	0.35	0.22	$T = 0.085C^{0.711}$	+65***	12.91	<0.001
TKN (kg/ha/year)	1.42	0.07	3.6	2.4	0.06	$T = 0.496C^{0.200}$	+76,361***	20.09	<0.001
TP (kg/ha/year)	0.186	0.021	0.462	0.412	0.017	$T = 0.068C^{0.720}$	+46,582***	16.87	<0.001
TSS (kg/ha/year)	36	2	64	65	2	$T = 0.762C^{0.547}$	+64,323***	11.42	<0.001
Cu (g/ha/year)	10	0.2	15	18	0.2	$T = 30.358C^{-0.078}$	+8,900***	10.65	<0.001
Pb (g/ha/year)	9	0.4	1	2	0.6	$T = 54.358C^{-0.064}$	$+163^{N.S.}$	1.07	0.389
Zn (g/ha/year)	82	0.6	55	17	2	$T = 34,215,540C^{-1.528}$	+8,650***	2.42	0.096

Notes: C = control; N.S. = not significant; T = treatment.
[1] n = number of samples; n for FC, and metals were three and seven, respectively.
[2] n for metals were 20.
*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$.

This paired watershed study demonstrates that the flow of stormwater runoff and the mass export of several pollutants can be significantly reduced by implementing LID practices when compared to traditional conveyance methods. As a result, LID stormwater treatment practices have the potential to improve water quality and runoff quantity in New England urban and suburban environments. More specifically, the method of analysis used by the Jordan Cove Study shows that percent change based on mass exports is a valid model for paired watershed comparisons, especially when benchmarked against the Long Island Sound TMDL of 58.5% reduction in nitrogen. Conversely, the annual total suspended solids (TSS) load increased after construction which does not comply with the Coastal Zone Act Reauthorization Amendments (CZARA) Section 6217 requirement to reduce annual TSS loads by 80% for new development (USEPA, 1993). Although this requirement was not met, the increase is explained by the research and provides some insight into future improvements in design standards.

Durham, NH Research Facility

The study site is located at the University of New Hampshire Stormwater Center in Durham, NH, on the perimeter of a 9-acre commuter parking lot (900 parking spaces). The contributing drainage area generates stormwater runoff typical of developed urban and suburban subwatersheds – contaminant concentrations are above or equal to national norms for parking lot runoff (Roseen et al., 2009). The parking lot is used to near capacity for nine months of the year, and the pavement is frequently plowed, salted and sanded during the winter. The climatology of the UNHSC study area is characterized as coastal, cool temperate forest, with an average annual precipitation of 122cm uniformly distributed throughout the year (Roseen et al., 2009). The field site contains three types of stormwater treatment systems (Figure 4-16): conventional, structural best management practices (swales, retention ponds), LID stormwater designs (tree filters, bioretention systems), and manufactured devices (hydrodynamic separators). The site was designed to test a range of stormwater treatment practices under the same conditions, with a single influent source providing nearly identical loading to each system (Roseen et al., 2009). The parallel, but separate configuration of the installed systems normalizes the variability that is typical in stormwater contaminant loading and regional rainfall characteristics (UNHSC, 2007).

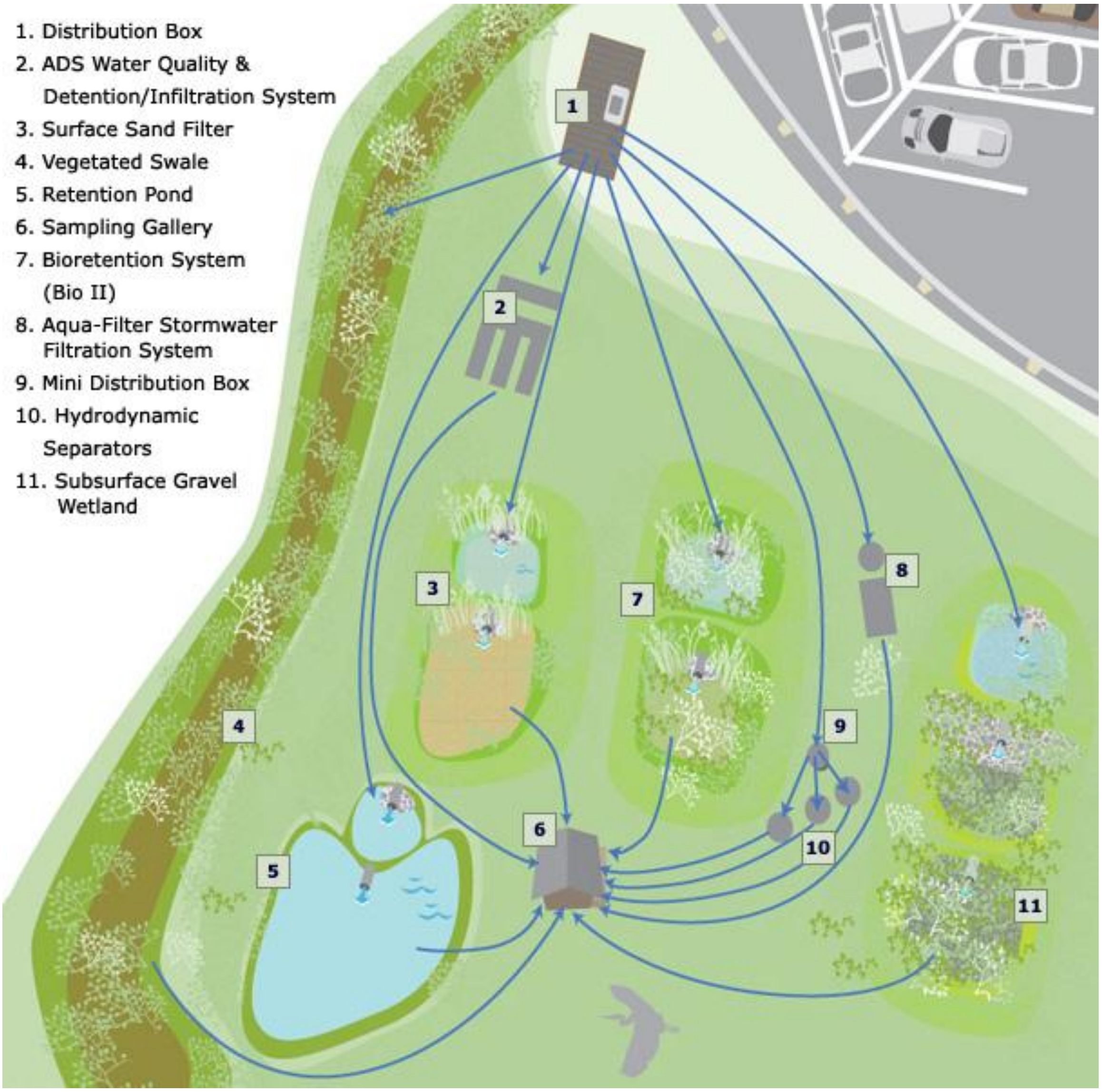


Figure 4-16: UNHSC Field Research Site (UNHSC, 2007)

Each treatment was uniformly sized (Table 4-16) to address a rainfall-runoff depth equivalent to 90% of the daily precipitation frequency: 1" of rainfall from 1-acre of impervious surface. In addition, all treatment systems have an impermeable liner to account for the flow of stormwater runoff through each of the systems, as well as the contaminants contained in the flow.

Table 4-16: Engineering Design Criteria for Stormwater Treatment Systems (UNHSC, 2007; Roseen et al., 2009)

Design Specification	Value (SI Unit)	Value (English unit)
Rainfall-Runoff Depth	2.54 cm	1 inch
Catchment Area	0.4 hectares	1 acre
Treatment Peak Flow	2,450 m^3/day	1 cfs
10-Year Peak Storm Flows	8,570 m^3/day	3.5 cfs
Treatment Volume	92 cubic meters	3,264 cubic ft
Treatment Volume Drain Time	24-48 hours	24-48 hours

Since 2004, the University of New Hampshire Stormwater Center has been evaluating performance of theses stormwater treatment systems based on the 6-step process identified in Figure 4-17. Stormwater runoff is directed to a single entry point to measure flow, pH, conductivity, dissolved oxygen, temperature, turbidity and numerous contaminants. Through a series of underground pipes, the runoff is then distributed evenly to each of the stormwater systems where it receives treatment. Stormwater runoff is then directed to a sampling gallery where the effluent is measured for flow, pH, conductivity, dissolved oxygen, temperature, turbidity and numerous contaminants. Automated samplers are used to collect samples at both influent and effluent locations.

1. Stormwater runoff from the nine-acre parking lot is channeled into a 36-inch pipe where influent (runoff) is monitored in real time for the following characteristics: flow, pH, conductivity, dissolved oxygen, temperature, and turbidity. At the same time, automated samplers collect samples of influent at discrete time intervals over the course of the rainfall's hydrograph. These samples are processed and evaluated for a range of contaminants, or frozen for future evaluation.

2. Stormwater then flows into a distribution box with a floor that rests slightly higher than the outlet invert elevations, which direct runoff to each of the stormwater treatments. This configuration insures that runoff will scour the floor of the box, thereby preventing the accumulation of sediment. Baffles and flow splitters help to equally and evenly distribute stormwater among treatments.

3. From the distribution box, runoff influent flows into a network of pipes and is distributed into each stormwater treatment.

4. Runoff influent moves through the stormwater treatments.

5. Runoff leaving the treatments (effluent) is conveyed by perforated subdrains into a sampling gallery.

6. In the sampling gallery, the effluent is monitored in real time for the following characteristics: flow, pH, conductivity, dissolved oxygen, temperature, and turbidity. Also in the gallery, automated samplers collect samples of runoff at discrete time intervals over the rainfall hydrograph. These samples are evaluated for the same range of contaminants to generate performance characterizations.

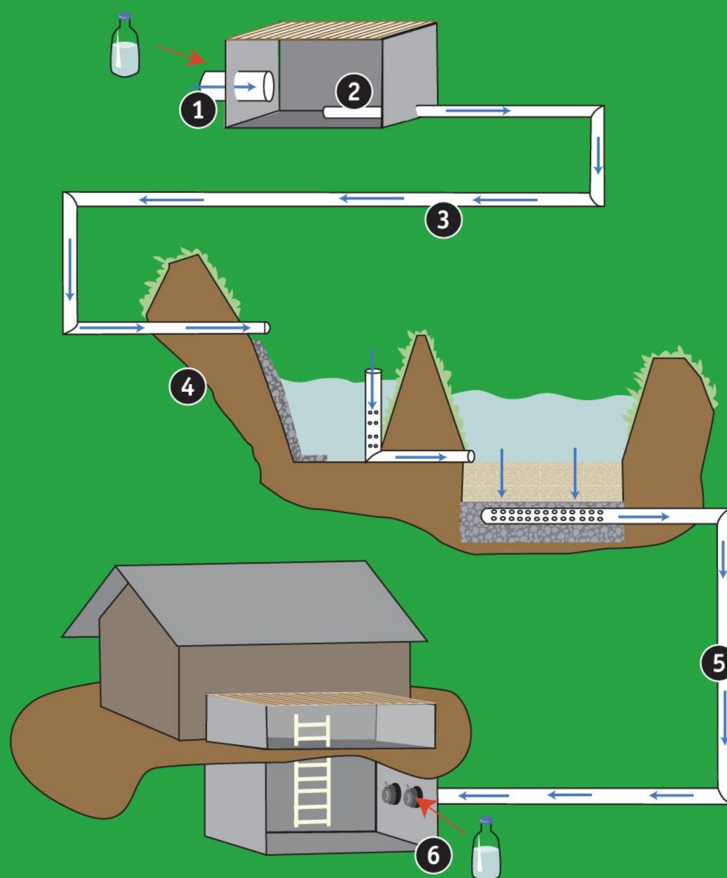


Figure 4-17: UNHSC 6-Step Performance Evaluation Process (UNHSC, 2007)

The University of New Hampshire Stormwater Center uses a standard benchmarking approach to compare the various systems tested on the research site where the variability that generally depicts removal efficiencies as an ineffective measure is normalized. Pollutant removal efficiency based on the Efficiency Ratio Method is used as the performance metric because the treatment systems receive the same quantity and quality of stormwater at the same time. Table 4-17 compares data on water quality treatment and runoff volume reduction performance of the stormwater treatment systems analyzed by UNHSC as of 2009. Water quality treatment performance is assessed by pollutant where percent reduction is recorded as a median value. Volume reduction is represented by percent average peak flow reduction and average lag time in minutes. The data collected and compiled by UNHSC also serves as the basis for further development of analytical models that can improve stormwater system design and water quality treatment performance. In comparison to the conventional and manufactured treatment devices, LID practices demonstrated better performance for volume reduction and pollutant removal capability for total petroleum hydrocarbons, dissolved inorganic nitrogen and total zinc. Nitrogen and phosphorus removal results were not as positive for the LID practices.

Table 4-17: UNHSC Pollutant Removal Efficiencies (UNHSC, 2010)

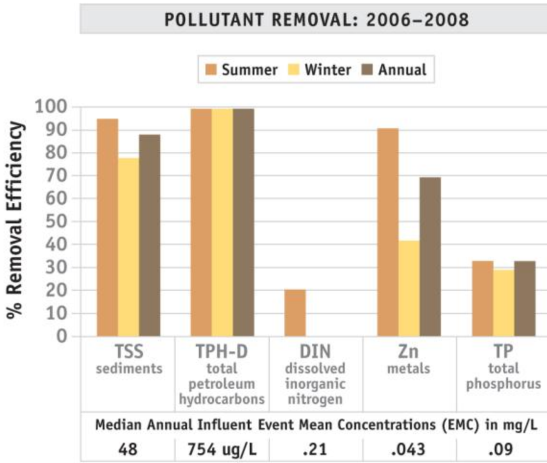
Treatment System	TSS (% Removal)	Total Petroleum Hydrocarbons (% Removal)	Dissolved Inorganic Nitrogen (% Removal)	Total Phosphorous (% Removal)	Total Zinc (% Removal)	Average Annual Peak Flow Reduction (% Removal)	Average Annual Lag Time (Minutes)
Conventional Treatment Devices							
Retention Pond	68	82	33	NT	68	86	455
Stone (rip-rap) Swale	50	33	NT	-	64	6	7
Vegetated Swale	58	82	NT	NT	88	52	38
Berm Swale	50	81	NT	8	50	24	58
Deep Sump Catch Basin	9	14	NT	NT	NT	NT	NT
Manufactured Treatment Devices							
ADS Infiltration Unit	99	99	NT	81	99	87	228
StormTech	80	93	NT	49	56	76	274
AquaFilter	62	26	NT	59	52	NT	NT
Hydrodynamic Separators	27	1	NT	42	24	NT	NT
Low Impact Development							
Surface Sand Filter	51	98	NT	33	77	69	187
Bioretention Cell 1 - 48" depth	97	99	44	-	99	75	266
Bioretention Cell 2 - 30" depth	87	99	NT	34	68	79	309
Gravel Wetland	99	99	98	56	99	87	251
Porous Asphalt	99	99	NT	60	75	82	1,275
Pervious Concrete	97	99	NT	NT	99	93	1,144
Tree Filter	93	99	3	NT	78	NT	62

Note: "NT" signifies no treatment, indicating the stormwater treatment did not remove the pollutant identified.

For the past few years, the University of New Hampshire Stormwater Center has assessed over twenty different stormwater treatment systems for their ability to improve water quality and reduce runoff volume during numerous storm and snowmelt events over a wide range of seasonal and storm characteristics. More specifically, the research conducted by UNHSC has shown that bioretention systems are most effective when they serve as local source control devices that intercept and manage less than 1-acre of impervious cover in a well-distributed network of runoff control measures (UNHSC, 2010). For treatment of larger impervious areas as an end-of-pipe system, a more complex design most likely will be needed when using bioretention as a practice for stormwater control.

The bioretention system at UNHSC (Figure 4-18) has shown consistent performance through 2008 in removing nearly all of the constituents commonly associated with stormwater treatment (Figure 4-19), as well as demonstrating a high capacity to reduce peak flows and runoff volume (Figure 4-20). However, low removal rates for nitrogen and phosphorus were observed during this period likely due to the soil media content (UNHSC, 2010). Variations of bioretention soil media are currently being studied in two new bioretention design applications at UNHSC to target further reduction of these two constituents (UNHSC, 2010).

Figure 4-18: Bioretention Cell at UNHSC (Roseen et al., 2006)



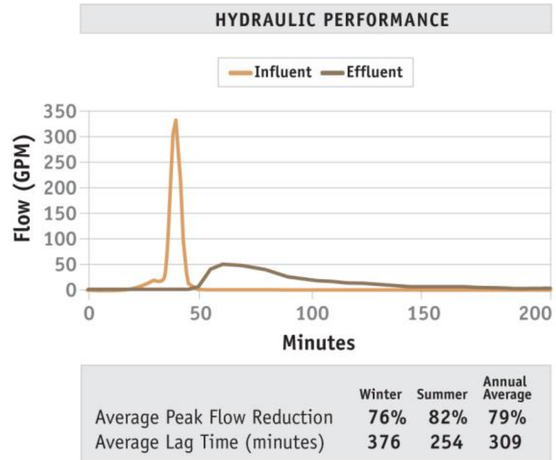


Figure 4-19: (Left) Pollutant Removal Performance for Bioretention Cell at UNHSC (UNHSC, 2010)
Figure 4-20: (Right) Hydraulic Performance for Bioretention Cell at UNHSC (UNHSC, 2010)

The Jordan Cove Watershed Project and the research facility at the University of New Hampshire Stormwater Center conducted site level LID monitoring studies that evaluated the water quantity and water quality performance of traditional and low impact development stormwater treatment practices. Compared to traditional stormwater controls, substantial decreases in volume reduction were demonstrated in both LID studies, indicating that LID practices function effectively and have a positive impact in New England urban environments. Volume reduction was also linked to load reductions for many of the constituents monitored. Although phosphorus and nitrogen showed increased exports in both LID studies, possible explanations were provided to understand the increases. At the UNHSC site, continued research is being conducted on new bioretention design applications to understand the implications of different soil media composition for retention of phosphorus and nitrogen. Both of these mechanisms should be used to further bioretention design standards and maintenance practices.

Summary

LID practices and bioretention are intentionally designed to disperse flows (avoid concentration) and infiltrate stormwater runoff, making monitoring quite challenging. First, LID practices and bioretention are less likely to have an influent stream that is conducive to inflow-outflow comparisons. And, secondly, the length of time required to obtain representative monitoring data to draw appropriate conclusions may be much longer than for conventional studies. Reduction in volume is the emphasis of LID practices and bioretention, rather than on the concentration of the pollutant being reduced. Therefore, flow monitoring is likely the most important aspect of performance monitoring. LID and bioretention studies without well designed and implemented hydrologic and hydraulic monitoring components would seem to be of little value to the research, design and technical communities.

Monitoring is a very challenging and complex process, and continues to evolve as more studies are conducted. The research and databases reviewed in this study highlight the fact that the technical and scientific communities are very interested in the subject of monitoring. There is much debate over the most appropriate method for analyzing and reporting water quality data. The research examined in this study identified the two most common approaches for evaluating the effectiveness of stormwater BMPs and LID performance – pollutant removal efficiency and effluent quality. Many researchers support the use of pollutant removal efficiency (as a mass/load calculation) because the reported removal rate is the actual pollutant load being reduced by the stormwater treatment practice over time and is useful in TMDL assessments, and depending on the number of storm events sampled, is most likely more representative of BMP performance over time (Claytor, 2002). This explanation supports the rationale as to why the majority of the LID and bioretention research studies investigated in this study present performance results as “Pollutant Removal Efficiency”. Conversely, the International Stormwater BMP Database advocates for the use of the “Effluent Probability Method”, which may be more suited to statistical analysis and BMP comparisons. Since volume reduction does not factor into this method, improvement to design guidance should be based more on mass balance methods that account for the natural processes that occur within the treatment practices themselves.

Is bioretention an effective stormwater control? This author believes so, especially because good performance results were reported for volume reduction and for some pollutants, namely heavy metals and petroleum hydrocarbons, and TSS in some cases. However, performance results for phosphorus and nitrogen are not yet at acceptable levels. It is clear that more research studies and changes to design standards are needed to continue with the efforts to solve water quality issues caused by urbanization and NPS pollution. Specific factors that warrant design consideration include bioretention sizing in the context of urban watersheds, and soil/filter media composition, depth and area of media.

CHAPTER 5

CONCLUSION

"If uncertainty and regular change are inevitable, then we must learn to be flexible and adaptable" (Lister, 2007).

Conclusion

This study sought to evaluate the performance of bioretention as an effective stormwater control for reducing stormwater runoff and improving water quality in New England urban environments. This research goal was accomplished by: (1) determining how stormwater best management practices (BMPs) and low impact development (LID) practices are selected for use in the environment; (2) classifying monitoring methods and identifying measurement criteria used by researchers and industry experts to evaluate performance; and (3) determining what, if any, limitations of these stormwater treatment practices are revealed through these monitoring efforts, particularly including performance in cold weather.

This study found that bioretention is a viable stormwater control option that manages urban runoff by reducing peak flows and volume, and removing or reducing nonpoint source (NPS) pollution. In addition, bioretention is a popular choice by communities because it is adaptable in many different applications and because bioretention provides multi-functional benefits to the environment and the general public (PGC, 2007). The decision to use bioretention is recommended to be based on analysis of site and climatic conditions that factor in specific design components such as drainage area size, land cover, ponding depth, soil depth, size of surface area and the expected infiltration rate to capture most, if not all, stormwater runoff to ensure that it receives the maximum treatment possible. Though each stormwater BMP and LID practice is unique, pollutant removal capabilities are highly correlated to the operation of the stormwater treatment practice and the physical, chemical and biological processes the treatment practice incorporates.

The effectiveness of stormwater BMP and LID performance is arguably best determined through monitoring efforts, of which there are many. The two most common approaches for evaluating the effectiveness of stormwater BMPs and LID performance – pollutant removal efficiency and effluent quality – were identified by this research. Currently, there is much discussion in the Civil/Environmental Engineering and Natural Resource Management industry, and in the research, as to whether pollutant removal efficiency is the best method for monitoring stormwater BMP and LID performance, despite the fact that most regulations require specific percentage reductions for target pollutants in Total Maximum Daily Loads (TMDLs). The effectiveness of stormwater BMPs and LID practices plays an integral role in assuring that TMDL goals are met for receiving waterbodies. Several factors contribute to the pollutant removal capability of the stormwater treatment practice – the estimated pollutant removal capability of the BMP, contributing drainage area, annual precipitation, BMP design criteria, BMP construction and implementation practices, and long-term maintenance (Claytor, 2002), as well as the physical, chemical and biological processes occurring within the treatment practice. In the final analysis, however, receiving water quality is affected more by the overall mass loading of pollutants than by any single storm event (UNHSC, 2010). Effluent quality was shown to be more suitable to statistical analysis and BMP comparisons than for determining pollutant removal performance.

Are there limitations in the performance of bioretention systems? Research studies demonstrated that on average 95-98% of stormwater runoff is captured by bioretention systems (Dietz and Clausen, 2005; Davis, 2008; Li et al., 2009; Hunt et al., 2006), and therefore the stormwater is infiltrated and evapotranspired. With respect to water quality improvement, good performance results were reported for some NPS pollutants, specifically heavy metals (zinc, lead, copper) and petroleum hydrocarbons, as well as total suspended solids in some cases. Where bioretention fell short was in the retention and/or removal of phosphorus and nitrogen, which is critical to the quality and health of downstream receiving waterbodies. Bioretention research studies, industry databases – International Stormwater BMP Database and National Pollutant Removal Performance Database, and LID monitoring case studies – Jordan Cove Watershed and the University of New Hampshire Stormwater Center, all confirmed this to be the case. This research also suggests that modification of bioretention soil media may improve the retention/removal performance of phosphorus and nitrogen. The literature shows concerns of cold weather performance; however, the composition of the bioretention media was credited for the continued infiltration of bioretention systems despite frozen conditions, as rapid thawing of the soil media occurs when runoff enters the bioretention system (Dietz, 2007; Roseen et al., 2009).

This study advocates for the increased use of bioretention in New England urban environments as an effective stormwater control to reduce urban runoff and reduce nonpoint source (NPS) pollution generated by urbanization. Although monitoring has proven to be complex and challenging, it is the best method for determining the effectiveness of stormwater treatment practices and pollutant removal performance.

Stormwater Best Management Practices (BMPs) and Low Impact Development (LID) performance results are also needed to direct improvements to design standards and guidance that aid and inform state and local municipalities in the proper selection of green infrastructure/stormwater controls.

Research studies need to continue to improve bioretention performance, especially given the fact that phosphorus and nitrogen loads are not sufficiently reduced by bioretention systems (Dietz and Clausen, 2006; Hunt et al., 2006; Li and Davis, 2009). Current design standards are inadequate to determine how best to optimize bioretention designs to enhance pollutant removal, as innovative technologies continue to evolve and as more is learned about the cumulative effects of nonpoint source (NPS) pollutants in downstream waterbodies. Additional research, monitoring and testing are clearly needed to supplement the existing knowledge base and to develop predictive methods for assessing alternative design strategies that target specific pollutants, like phosphorus and nitrogen. Perhaps it's time for a change, a different approach that allows adaptability and modification within the process itself.

Contributions to the Field

Instituting "safe-to-fail" experiments is an approach that could be used to develop, test and advance best practice(s) (Lister, 2007) for application to stormwater management controls. The idea would be to develop a monitoring program for innovative, pilot projects that is integrated into an adaptive management process that is based on what is learned through the experimental design and testing process. In essence, design innovation would be pursued through responsible experimentation which fosters a different culture for monitoring and learning from both modest failures and successes

(Ahern, 2011). Additionally, this approach would also require a transdisciplinary collaboration of research, science and practice professionals be formed to develop a sustainable long-term monitoring process.

The status quo or reactive approach can no longer be the normal response to protecting our water resources. The inherent risk of failure, fear of liability, conservative culture, and/or the unwillingness of local governments to budget and fund monitoring efforts must not impede the path to innovative and successful resolution of water quality impairment. Responsible adaptive environmental management must be incorporated at the beginning of the experimental design process, during the design phase and post implementation (Holling, 1986) to be effective. Under this adaptive model, researchers, scientists and practice professionals gain new knowledge through monitoring and analysis of the design experiments, and "learning from change" (Holling, 1986) influences how monitoring experiments are conducted and design guidance is modified in the future to target the removal of specific nutrients/pollutants in urban runoff. An example of the adaptive planning and design model is at the University of New Hampshire Stormwater Center where knowledge of phosphorus and nitrogen removal data from their research monitoring program is being used to modify soil/filter media and content in bioretention design.

The proposed monitoring approach would be based on an iterative design process that uses a stormwater control, like bioretention, to target reduction of a specific pollutant. For example, excessive loads of phosphorus in stormwater runoff are known to accelerate the eutrophication process in downstream waterbodies; therefore, phosphorus would likely be the first nutrient that a "safe-to-fail" experiment is designed for. Since water and soil chemistry are likely more important for phosphorus removal than biological activity (GC&WWE, 2010), bioretention design considerations of the "safe-to-fail" experiment should focus on the bioretention media/soil properties for the physical removal of phosphorus – low P-index soils (Hunt et al., 2006) and organic material with high cation exchange capacity like hemic peat (Hunt et al., 2006; CWP, 2010; GC&WWE, 2010). Periodic soil testing and annual maintenance practices during the monitoring period become important in this experiment since the remediation occurs in the surface and soil media layers.

The experimental process would continue until the phosphorus removal rate is at an acceptable load level, and no adverse effects were observed for other constituents previously under control prior to the start of the experiment. The next nutrient that a "safe-to-fail" experiment within the same bioretention system could be designed for is nitrogen. As previously discussed, ammonification, nitrification, denitrification and plant uptake are the primary removal mechanisms; therefore, biological activity becomes the important design component to address removal of the multiple forms of nitrogen. Additional bioretention design considerations to remove nitrogen may consist of: fill media soil organic content; hydraulic conductivity; increasing depth and area of media; adding soil amendments; and, changing the mulch layer. Adding anaerobic zones enhances the denitrification process and can be facilitated by an underdrain that is elevated from the bottom of the bioretention cell and within a gravel blanket (PSAT, 2005). Harvesting the vegetation and removal of captured sediment may be key maintenance practices that aid in the reliable removal of nitrogen (GC&WWE, 2010).

Annual soil testing would be integral to the continued monitoring of a bioretention cell. Testing for phosphorus and nitrogen should be a component of standard soil testing. A standardized maintenance program should be implemented to complement the monitoring process, and should include clearing flow paths, checking surface water storage capacity and mulching to reduce weeds and the need for mowing. Together, this maintenance program is planned to increase bioretention performance. As the exact nature and impact of bioretention continues to evolve, maintenance will dictate long-term performance and life-cycle costs. Use of bioretention systems to manage stormwater runoff and improve water quality should grow as design guidance matures, and as a result of continued research and applications.

As new experimental sites are tested, and new knowledge is generated from the bioretention experimental studies, the “safe-to-fail” experiments would begin to anticipate failures and monitor the effectiveness of a specific bioretention design component in the removal of certain nutrients/pollutants. This new knowledge would then be applied to the next designed “safe-to-fail” experiment so that the designed experiment contains and minimizes failures (Steiner, 2006), and measures how the new knowledge or newly incorporated bioretention design components operate in the designed “safe-to-fail” experiment. Future design experiments could then be structured to prepare, plan and adapt for when a system fails (Ahern, 2010) and to demonstrate how stormwater BMPs or LID practices can be used to treat impaired receiving waterbodies. The case of the Chicago, IL Green Alleys program is an example of where innovative stormwater solutions were implemented to alleviate flooding and reduce the risk of combined sewer overflows.

Future Research Needs

This study has shown that more research studies are needed to facilitate changes to design standards in order to solve water quality issues caused by urbanization and NPS pollution. Three areas identified in this study include soil testing, groundwater testing and the need for more bioretention studies in other parts of the United States.

Collection of soil and infiltration samples becomes increasingly important in infiltration-oriented stormwater treatment practices, like bioretention. This type of sampling is helpful in assessing the depth and the extent of pollutant accumulation in soil layers and the relationship of pollutants in groundwater, as well as documenting soil chemical properties for identifying factors that are influencing the system's performance (GC&WWE, 2009). Soil characteristics in amended soils for instance, affect infiltration rates and nutrient loading. Therefore, to further the understanding of the life cycle and maintenance requirements of bioretention systems, more intensive soil testing and monitoring is required to provide up-to-date information on the fate and transport of pollutants. In addition, studying natural soil profiles (in conjunction with Natural Resource Conservation Service (NRCS) soil scientists) that reveal favorable water and nutrient retention attributes could also serve as a model or natural prototype for designing the layering and composition of constructed soils in bioretention systems.

This study identified two additional areas that could potentially lead to increased performance of bioretention for improving water quality in New England urban environments. Maintaining groundwater recharge is an emerging issue of stormwater control, especially considering that many states and local jurisdictions do not have requirements or stormwater management standards to maintain groundwater recharge

(Davis et al., 2009). Groundwater sampling could help answer important questions about the fate and transport of pollutants as a result of increased usage of LID and bioretention infiltration practices. In addition, most of the research reviewed in this study was from the eastern United States (U.S.). Application of bioretention in other regions of the U.S. (extremely cold regions to hot/dry/humid/tropical regions) could guide future design changes that address bioregional and seasonal variations. Stormwater BMPs and LID practices will continue to evolve as research identifies new environmental concerns and stormwater controls, and play a key role in addressing water quality concerns in urbanized watersheds in New England.

APPENDIX A

MASSACHUSETTS WATER QUALITY PROGRAM

The Massachusetts Department of Environmental Protection (MassDEP) has the duty and responsibility for protecting the public health and improving the quality and value of the water resources of the Commonwealth. To restore and maintain the integrity of Massachusetts's waterbodies, MassDEP has adopted the Massachusetts Surface Water Quality Standards. These standards designate the most sensitive uses for which the various waters shall be enhanced, maintained and protected (Table A-1); prescribe the minimum water quality criteria required to sustain these designated uses (Table A-2); and, contain the regulations necessary to achieve the designated uses and maintain existing water quality (CM DWPC, 2010). Note that the water quality criteria for "nutrients" applies to all surface waters regardless of class, and is stipulated as none in concentrations that would cause or contribute to impairment of existing or designated uses unless naturally occurring, and shall not exceed the site specific criteria developed in a TMDL or otherwise established by MassDEP (CM DWPC, 2010). Point and nonpoint source discharges shall be treated with BMPs to ensure protection of existing and designated uses (CM DWPC, 2010).

Table A-1: Surface Water Classifications for Massachusetts (CM DWPC, 2010)

MA Water Type	Water Classification	Class Description
Inland Water Class	A	These waters include waters designated as sources of public water supply and their tributaries, and designated as excellent habitats for fish, other aquatic life and wildlife, and primary & secondary recreation. These waters are protected as Outstanding Resource Waters.
	B	These waters are designated as habitats for fish, other aquatic life and wildlife, and primary & secondary recreation. Where designated, they shall be suitable as sources of public water supply, and suitable for irrigation, agriculture and industrial uses.
	C	These waters are designated as habitats for fish, other aquatic life and wildlife, and secondary recreation. They shall also be suitable for irrigation and industrial uses.
Coastal and Marine Classes	SA	These waters are designated as excellent habitats for fish, other aquatic life and wildlife, and primary & secondary recreation. Where designated, they shall also be suitable for shellfish harvesting without depuration.
	SB	These waters are designated as habitats for fish, other aquatic life and wildlife, and primary & secondary recreation. Where designated, they shall also be suitable for shellfish harvesting without depuration.
	SC	These waters are designated as habitats for fish, other aquatic life and wildlife, and secondary recreation. They shall also be suitable for industrial cooling and process uses.

Table A-2: Massachusetts Surface Water Classifications and Criteria (CM DWPC, 2010)

Classification	Parameter	Criteria
A	Aesthetics	Excellent.
	Dissolved Oxygen	Not less than 6mg/L in cold water fisheries & not less than 5.0mg/L in warm water fisheries.
	Suspended & Settleable Solids	None in concentrations or combinations that would impair designated uses, physical/chemical composition of the bottom, or aquatic organisms living in or on the bottom substrate.
	Bacteria	Water intakes in unfiltered public water supplies: fecal coliform shall not exceed 20 fecal coliform organisms per 100ml or total coliform shall not exceed 100 organisms per 100ml in 6-month period; Beaches: no single sample of E. coli or enterococci shall exceed 235 or 61 colonies, respectively, per 100ml during a bathing season or seasonally during the non-bathing season.
	Color & Turbidity	None in concentrations or combinations that would impair designated uses.
	pH	6.5 - 8.3 but no more than .5 units outside the range; no change from natural background conditions.
	Allowable Temperature Increase	No changes from natural conditions, and shall not exceed 68°F in cold water fisheries, 83°F in warm water fisheries, and 1.5°F rise in temperature from discharges.
	Oil & Grease	None in concentrations or combinations which would be harmful to designated uses.
B	Aesthetics	Consistently good.
	Dissolved Oxygen	Not less than 6mg/L in cold water fisheries & not less than 5.0mg/L in warm water fisheries.
	Suspended & Settleable Solids	None in concentrations or combinations that would impair designated uses, physical/chemical composition of the bottom, or aquatic organisms living in or on the bottom substrate.
	Bacteria	Beaches: no single sample of E. coli or enterococci shall exceed 235 or 61 colonies, respectively, per 100ml during a bathing season or seasonally during the non-bathing season.
	Color & Turbidity	None in concentrations or combinations that would impair designated uses.
	pH	6.5 - 8.3 and not more than .5 units outside range; no change from natural background conditions.
	Allowable Temperature Increase	No changes from natural conditions, and shall not exceed 68°F in cold water fisheries & 83°F in warm water fisheries. Rise in temperature due to discharge shall not exceed 3°F in cold water fisheries or 5°F for warm water fisheries.
	Oil & Grease	None in concentrations or combinations which would be harmful to designated uses.
C	Aesthetics	Good.
	Dissolved Oxygen	Not less than 5mg/L at least 16-hrs of any 24-hr period & not less than 3mg/L at any time.
	Suspended & Settleable Solids	None in concentrations or combinations which would impair designated uses, physical/chemical composition of the bottom, or aquatic organisms living in or on the bottom substrate.
	Bacteria	The geometric mean of all E. coli samples taken in recent 6-month period shall exceed 630 colonies per 100ml, and 10% of such samples shall not exceed 1260 colonies per 100ml - seasonally at the discretion of MassDEP.
	Color & Turbidity	None in concentrations or combinations that would impair designated uses.
	pH	6.5 - 9.0 and not more than 1.0 standard units outside range; no change from natural background conditions.
	Allowable Temperature Increase	No changes from natural conditions, and shall not exceed 85°F nor shall the rise due to a discharge exceeding 5°F.
	Oil & Grease	None in concentrations or combinations which would be harmful to designated uses.

Table A-2: Massachusetts Surface Water Classifications and Criteria (CM DWPC, 2010) (continued from previous page)

Classification	Parameter	Criteria
SA	Aesthetics	Excellent.
	Dissolved Oxygen	Not less than 6mg/L at any time.
	Suspended & Settleable Solids	None in concentrations or combinations which would impair designated uses, physical/chemical composition of the bottom, or aquatic organisms living in or on the bottom substrate.
	Bacteria	Shellfishing: fecal coliform shall not exceed a geometric mean Most Probable Number (MPN) of 14 organisms per 100ml, nor shall more than 10% of samples exceed a MPN of 28/100ml; Bathing & Non-Bathing Beaches: no single enterococci sample shall exceed 104 colonies per 100ml and the geometric mean of recent 5 samples shall not exceed 35/100ml during bathing and non-bathing seasons - applied at the discretion of MassDEP.
	Color & Turbidity	None in concentrations or combinations that would impair designated uses.
	pH	6.8 - 8.5 and not more than .2 standard units outside range.
	Allowable Temperature Increase	No changes from natural conditions, and in no case exceed 85°F nor a maximum daily mean of 80°F, and rise in temperature from discharge shall not exceed 1.5°F.
	Oil & Grease	None in concentrations or combinations which would be harmful to designated uses.
SB	Aesthetics	Consistently good.
	Dissolved Oxygen	Not less than 5mg/L at any time.
	Suspended & Settleable Solids	None in concentrations or combinations which would impair designated uses, physical/chemical composition of the bottom, or aquatic organisms living in or on the bottom substrate.
	Bacteria	Shellfishing: fecal coliform shall not exceed a median or geometric mean Most Probable Number (MPN) of 88 organisms per 100ml; Bathing & Non-Bathing Beaches: no single enterococci sample shall exceed 104 colonies per 100ml and the geometric mean of recent 5 samples shall not exceed 35/100ml during bathing and non-bathing seasons - applied at the discretion of MassDEP.
	Color & Turbidity	None in concentrations or combinations that would impair designated uses.
	pH	6.8 - 8.5 and not more than .2 standard units outside range; no change from natural background conditions.
	Allowable Temperature Increase	No changes from natural conditions, and in no case exceed 85°F nor a maximum daily mean of 80°F and rise in temperature from discharge shall not exceed 1.5°F during July-September nor 4°F during October - June.
	Oil & Grease	None in concentrations or combinations which would be harmful to designated uses.
SC	Aesthetics	Good.
	Dissolved Oxygen	Not less than 5mg/L at least 16-hrs of any 24-hr period & not less than 4mg/L at any time.
	Suspended & Settleable Solids	None in concentrations or combinations which would impair designated uses, physical/chemical composition of the bottom, or aquatic organisms living in or on the bottom substrate.
	Bacteria	The geometric mean of all E. coli samples taken in recent 6-month period shall not exceed 175 colonies per 100ml, and 10% of such samples shall not exceed 350 colonies per 100ml - seasonally at the discretion of MassDEP.
	Color & Turbidity	None in concentrations or combinations that would impair designated uses.
	pH	6.5 - 9.0 and not more than .5 standard units outside range; no change from natural background conditions.
	Allowable Temperature Increase	No changes from natural conditions, and in no case exceed 85°F nor the rise from discharge exceed 5°F.
	Oil & Grease	None in concentrations or combinations which would be harmful to designated uses.

As evidence in Table A-2 above, effective water quality management is largely dependent upon prevention and control of NPS pollution within the waterbodies of Massachusetts. Through endorsement by the USEPA, Massachusetts has adopted a comprehensive watershed approach to planning and implementing water resource protection activities throughout the state (MassDEP, 2008a). In 1993, twenty-seven major watersheds and coastal drainage areas were placed on a rotating 5-year schedule for monitoring, assessment, TMDL development, surface water permitting and NPS pollution control (Figure A-1) (MassDEP, 2008a). This holistic watershed-based program is meant to be an iterative process in protecting waterbodies that meet water quality standards, through the following phases (MassDEP, 2008a):

- During the first phase, existing water resource information is reviewed and water quality issues are identified to establish the basis for planning in the future.

- The second phase consists of water quality monitoring surveys that collect physical, chemical and biological water-resource data for activities that are implemented in accordance with the 5-year watershed monitoring schedule.

- The third phase of the watershed management approach involves a comprehensive analysis of the data and information assembled during the previous phases as a prerequisite to implementing corrective actions aimed at bringing impaired waters into compliance with water quality standards, which also forms the basis of the 305(b) and 303(d) reports.

- The implementation of control strategies for correcting water quality impairments constitutes the fourth phase of the watershed management approach, which is aimed at the reduction of pollutant loads to surface waters, including TMDL development, permit issuance and grant awards.

- The final phase of the watershed management approach is an evaluation of how successfully this program has addressed the water resource issues so that adjustments may be made during the next watershed management cycle.

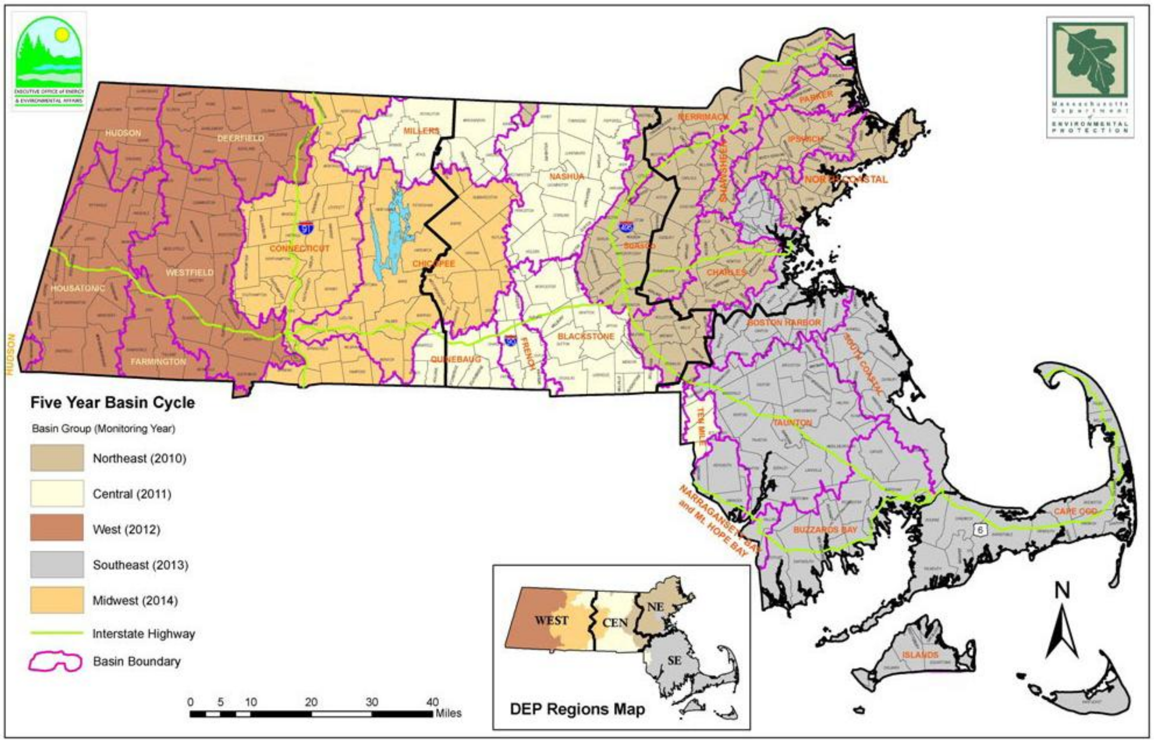


Figure A-1: MassDEP 5-Year Rotating Watershed Monitoring Cycle (MassDEP, 2010)

The MassDEP developed the Water Quality Monitoring Strategy (2005) to fulfill the monitoring requirements of the Clean Water Act to ensure the quality and value of the water resources for the Commonwealth of Massachusetts is clean and safe. This comprehensive monitoring program supports the management of water quality and applies to rivers, lakes and coastal areas, as well as groundwater. The major goals of this monitoring strategy and the resultant monitoring program elements designed to meet those goals are presented in Table A-3. In support of the 5-year rotating monitoring program, the highest priority monitoring efforts are directed towards recognizing the condition of surface waters, identifying the pollution sources related to TMDLs and developing strategies to restore impaired waters.

Table A-3: Massachusetts Water Quality Monitoring Strategy Goals and Design Elements (MassDEP, 2005)

Number	Monitoring Goals	Monitoring Design Elements
1	Determine whether waters are meeting Water Quality Standards.	• 5-year rotating watershed monitoring • Target monitoring to assess bioaccumulation • Target monitoring of lakes • Probabilistic Sampling Network
2	Determine water quality trends and contaiminant loadings.	• Continuous fixed-site monitoring network
3	Implement pollution control strategies (TMDLs and Cleanup Plans)	• Target monitoring to support TMDL Program • Target monitoring of lakes • Target monitoring to locate sources of bacterial contamination
4	Identify emerging issues and develop policies and standards.	• Target monitoring for criteria development
5	Measure program or project effectiveness.	• Project-specific, targeted monitoring
6	Improve the protection of public health and the environment by reducing the risk of drinking contaminated water.	• Surface Water Assessment Program • Probablistic monitoring of groundwater

In addition, the Massachusetts Department of Environmental Protection (MassDEP) applies stormwater management standards under the authority of the Wetlands Protection Act and the Massachusetts Clean Waters Act (MassDEP, 2008b). These “Stormwater Management Standards” address water quality and water quantity by establishing ten standards that require the implementation of innovative stormwater management strategies – stormwater BMPs and LID techniques (MassDEP, 2008b), as follows:

1. No new stormwater conveyances, like outfalls, may discharge untreated stormwater directly to or cause erosion in wetlands or waters of the Commonwealth of Massachusetts.
2. Manage peak discharges to pre-development levels (i.e., 1/2-1” rainfall).
3. Provide recharge through the use of infiltration measures.
4. Reduce Total Suspended Solids (TSS) – 80% removal rate.
5. Prevent pollution from land uses with higher potential pollutant loads to eliminate or reduce discharge of stormwater runoff.
6. Protect critical areas from stormwater discharges.

7. Redevelopment Project: meet standards to maximum extent practicable AND improve existing conditions.
8. Control construction-related impacts during construction and land disturbance activities.
9. Provide operation and maintenance.
10. Remove illicit discharges.

Stormwater runoff from all industrial, commercial, institutional, office, residential and transportation projects is to be managed according to these standards through the use of environmentally sensitive site designs that incorporate low impact development techniques to prevent the generation of stormwater and NPS pollution (MassDEP, 2008b). In addition, MassDEP has established a "LID Site Design Credit" to encourage developers to incorporate LID techniques in their developments to reduce or eliminate traditional BMPs used for treating and infiltrating stormwater (MassDEP, 2008b).

In 2009, MassDEP announced that it was proposing new stormwater regulations for inclusion into the Code of Massachusetts Regulations (MassDEP, 2009). The proposed regulations would establish a statewide general permit (SWGP) program aimed at controlling discharge of stormwater runoff from all privately-owned sites containing five or more acres of impervious surfaces in the state to: (1) apply for and obtain coverage under a general permit; (2) implement nonstructural BMPs for managing stormwater; (2) install LID techniques and structural stormwater BMPs at sites undergoing development or redevelopment; and, (4) submit annual compliance certifications to MassDEP. In the Charles River Watershed and other watersheds recognized as impaired – subject to total maximum daily load (TMDL) restrictions and contain phosphorous loads of 65% or greater, impervious surfaces of two or more acres are also subject to the proposed ruling. This proposed regulatory structure would shift much of the burden of managing stormwater from local municipalities to private property owners. As such, MassDEP received over 200 comments voicing concerns primarily directed at cost, aggregation of commonly managed properties under one permit, and the redevelopment threshold (MassDEP, 2009). A second round of public hearings is expected.

APPENDIX B

CONNECTICUT WATER QUALITY PROGRAM

The State of Connecticut has developed Water Quality Standards (WQS) in response to and in accordance with the Connecticut's Clean Water Act, which sets the broad outline and legal framework for Connecticut's entire program (CTDEP, 2011). Three elements make up Connecticut's WQS: (1) the standards themselves, (2) the criteria describing the allowable parameters and goals for various classifications (Table B-1), and (3) the class categories assigned to each surface and groundwater resource throughout Connecticut based on designated use (Table B-2) (CTDEP, 2011). These WQS provide policy guidance and serve many different purposes (CTDEP, 2011) as follows:

- Provide guidance about existing water quality in the state as well as DEP's goals for maintaining or improving that quality;
- Indicate the general types of discharges allowed;
- Ensure the segregation of drinking water supplies from waters used for waste assimilation;
- Show areas of conflict between usages, and areas where ground and surface waters are degraded;
- Provide the standards for toxicity consideration to protect aquatic life;
- Provide a framework for the establishment of priorities for pollution abatement, dispensation of State funding, remediation goals; and,
- Provide clear guidance for location decisions for business and industry as well as other economic developments.

Table B-1: Connecticut Surface Water Classifications and Criteria (CTDEP, 2011)

Classification	Parameter	Criteria
AA	Aesthetics	Uniformly excellent.
	Dissolved Oxygen	Not less than 5mg/L at any time.
	Sludge Deposits	None other than of natural origin.
	Suspended & Settleable Solids	None in concentrations or combinations which would impair designated uses, physical/chemical composition of the bottom, or aquatic organisms living in or on the bottom substrate.
	Silt/Sand Deposits	None other than of natural origin, except from agriculture, road maintenance, construction activity or dredging activity.
	Turbidity	Not to exceed 5 NTU (Nephelometric Turbidity Unit) over ambient levels and levels necessary to protect and maintain all designated uses.
	pH	As naturally occurs.
	Allowable Temperature Increase	No changes from natural conditions, and in no case exceed 85°F or raise surface water temperature by more than 4°F.
	Chemical Constituents	None in concentrations or combinations which would be harmful to designated uses.
	Nutrients	Loading of nutrients (phosphorus & nitrogen) shall not exceed that which supports maintenance or attainment of designated uses.
	Sodium	Not to exceed 20mg/L.
A	Aesthetics	Uniformly excellent.
	Dissolved Oxygen	Not less than 5mg/L at any time.
	Sludge Deposits	None other than of natural origin.
	Suspended & Settleable Solids	None in concentrations or combinations which would impair designated uses, physical/chemical composition of the bottom, or aquatic organisms living in or on the bottom substrate.
	Silt/Sand Deposits	None other than of natural origin, except from agriculture, road maintenance, construction activity or dredging activity.
	Turbidity	Not to exceed 5 NTU (Nephelometric Turbidity Unit) over ambient levels and levels necessary to protect and maintain all designated uses.
	pH	As naturally occurs.
	Allowable Temperature Increase	No changes from natural conditions, and in no case exceed 85°F or raise surface water temperature by more than 4°F.
	Chemical Constituents	None in concentrations or combinations which would be harmful to designated uses.
	Nutrients	Loading of nutrients (phosphorus & nitrogen) shall not exceed that which supports maintenance or attainment of designated uses.
	Sodium	None other than of natural origin.

Table B-1: Connecticut Surface Water Classifications and Criteria (CTDEP, 2011)
(continued from previous page)

Classification	Parameter	Criteria
B	Aesthetics	Good to excellent.
	Dissolved Oxygen	Not less than 5mg/L at any time.
	Sludge Deposits	None except for small amounts permitted waste treatment facility discharge and levels needed to protect and maintain all designated uses.
	Suspended & Settleable Solids	None in concentrations or combinations which would impair designated uses, physical/chemical composition of the bottom, or aquatic organisms living in or on the bottom substrate.
	Silt/Sand Deposits	None other than of natural origin, except from agriculture, road maintenance, construction activity or dredging activity.
	Turbidity	Not to exceed 5 NTU (Nephelometric Turbidity Unit) over ambient levels and levels necessary to protect and maintain all designated uses.
	pH	6.5 - 8.0
	Allowable Temperature Increase	No changes from natural conditions, and in no case exceed 85°F or raise surface water temperature by more than 4°F.
	Chemical Constituents	None in concentrations or combinations which would be harmful to designated uses.
	Nutrients	Loading of nutrients (phosphorus & nitrogen) shall not exceed that which supports maintenance or attainment of designated uses.
	Sodium	None other than of natural origin.
SA	Aesthetics	Uniformly excellent.
	Dissolved Oxygen	Not less than 3mg/L at any time.
	Sludge Deposits	None other than of natural origin.
	Suspended & Settleable Solids	None other than of natural origin.
	Silt/Sand Deposits	None other than of natural origin, except from agriculture, road maintenance, construction activity or dredging activity.
	Turbidity	None other than of natural origin, except from agriculture, road maintenance, construction activity or dredging activity.
	pH	6.8 - 8.5
	Allowable Temperature Increase	No changes from natural conditions, and in no case exceed 83°F or raise surface water temperature by more than 4°F. During July-September, the temperature of the receiving water shall not be raised by more than 1.5°F unless there's no effect of spawning and growth of indigenous organisms.
	Chemical Constituents	None in concentrations or combinations which would be harmful to designated uses.
	Nutrients	Loading of nutrients (phosphorus & nitrogen) shall not exceed that which supports maintenance or attainment of designated uses.
	Sodium	None other than of natural origin.

Table B-1: Connecticut Surface Water Classifications and Criteria (CTDEP, 2011) (continued from previous page)

Classification	Parameter	Criteria
SB	Aesthetics	Good to excellent.
	Dissolved Oxygen	Not less than 3mg/L at any time.
	Sludge Deposits	None except for small amounts permitted waste treatment facility discharge and levels needed to protect and maintain all designated uses.
	Suspended & Settleable Solids	None in concentrations or combinations which would impair designated uses, physical/chemical composition of the bottom, or aquatic organisms living in or on the bottom substrate.
	Silt/Sand Deposits	None other than of natural origin, except from agriculture, road maintenance, construction activity or dredging activity.
	Turbidity	None other than of natural origin, except from agriculture, road maintenance, construction activity, discharge from waste treatment facility, or dredging activity.
	pH	6.8 - 8.5
	Allowable Temperature Increase	No changes from natural conditions, and in no case exceed 83°F or raise surface water temperature by more than 4°F. During July-September, the temperature of the receiving water shall not be raised by more than 1.5°F unless there's no effect of spawning and growth of indigenous organisms.
	Chemical Constituents	None in concentrations or combinations which would be harmful to designated uses.
	Nutrients	Loading of nutrients (phosphorus & nitrogen) shall not exceed that which supports maintenance or attainment of designated uses.
	Sodium	None other than of natural origin.

Table B-2: Designated Uses for Surface Waters in Connecticut (CTDEP, 2008)

CT Designated Use	Applicable Class of Water or Class Goal	Functional Definition
Recreation	AA, A, B, SA, SB	Swimming, water skiing, surfing or other full body contact activities, as well as boating, canoeing, kayaking, fishing, aesthetic appreciation or other activities that do not require fully body contact.
Habitat for Aquatic Life and Wildlife	AA, A, B, SA, SB	Waters suitable for the protection, maintenance and propagation or a viable community of aquatic life and associated wildlife.
Fish Consumption	AA, A, B, SA, SB	Waters supporting fish that do not contain concentrations or contaminants from local sources, which would limit consumption to protect human health.
Shellfish Harvesting for human consumption	SA	Waters from which shellfish can be harvested both recreationally and commercially, and consumed directly without depuration or relay. Waters may be conditionally approved.
Shellfish Harvesting for commercialization	SB	Waters supporting commercial shellfish harvesting for transfer to a depuration play or relay to approved areas for purification prior to human consumption.
Existing/Proposed Drinking Water Supplies	AA	Waters presently used for public drinking water supply or officially proposed for future public water supply.
Potential Drinking Water Supplies	A	Waters that have not been officially identified, but may be considered for public drinking water supply in the future.
Navigation	AA, A, B, SA, SB	Waters capable of being used for shipping, travel/other transportation by private, military or commercial vessels.
Industry	AA, A, B, SA, SB	Waters suitable for industrial supply.
Agriculture	AA, A, B	Waters suitable for general agricultural purposes.

The State of Connecticut Department of Environmental Protection (CTDEP) is also responsible for implementing federal regulations pertaining to water resources protection. Several federal and state regulatory programs are currently in place for stormwater quality management and water resource protection within the state. Table B-3 summarizes existing regulatory programs that address management of stormwater discharges in Connecticut. Under the Connecticut Clean Water Act, CTDEP has the regulatory authority to: (1) abate, prevent or minimize all sources of water pollution, including NPS pollution; (2) develop state water quality standards; (3) permit discharges, including stormwater discharges, to waters of the state under a series of general permits based on the type of activity; and, (4) establish enforcement tools for pollution abatement and prevention.

Table B-3: Existing Connecticut Stormwater Management Programs (Source: CTDEP, 2004)

Program	Program Goals	Stormwater Regulation	Regulates Quantity?	Regulates Quality?	State or Local Regulations	Regulation of New/Existing Facilities
Commercial General Permit	Regulates stormwater from commercial activity	Requires permits from a commercial activity with 5 or more acres of contiguous impervious surfaces	No	Yes	State	Both
Industrial General Permit	Regulates stormwater from industrial activity	Requires permits for facilities having a stormwater discharge associated with industrial activity	No	Yes	State	Both
Construction General Permit	Regulates stormwater from construction activity	Requires permits for construction activities disturbing 5+ total acres land area (1-5 acres regulated at local level under NPDES Phase II)	No	Yes	State	Both
Phase II General Permits	Regulates stormwater discharges from municipal, state & other designated stormwater drainage systems in urbanized areas	Requires municipalities & other entities to develop & implement a stormwater mgmt. program consisting of minimum control measures	Yes	Yes	State	Both
Inland Wetlands & Watercourses Act	Protects & regulates activities in inland wetlands, watercourse & adjacent areas	Considers impact to wetlands from stormwater or stormwater-related activities	Yes	Yes	State & Local	Both
Erosion & Sediment Guidelines	Provides guidance on erosion control	Guidelines for control of stormwater during construction	Yes	Yes (sediment)	State & Local	New
Flood Management	Regulates state actions in floodplains & changes in drainage patterns	Requires careful planning & siting of development projects & modifications to flood control facilities	Yes	Yes	State	Both
Stream Channel Encroachment Program	Regulates activities in certain floodplains	Considers impacts to wetlands & watercourses from stormwater or stormwater-related activities	Yes	Yes	State	Both
401 Water Quality Certification	Regulates activities which require a federal license or permit for discharge into state navigable waters	Requires certification from DEP that the discharge will comply with the Federal Water Pollution Control Act & CT Water Quality Standards	No	Yes	State/Federal	Both
Water Diversion	Regulates withdrawal & use of groundwater & surface waters of the state, including stormwater diversions	Requires permitting for any activity that causes, allows or results in the withdrawal from or the alteration, modification or diminution of the instantaneous flow of water, including stormwater	Yes	Yes	State	Both
Nonpoint Source Management Program	Coordinates statewide efforts to prevent & manage NPS pollution	Relies on existing regulations in place at federal, state & local levels	No	No	State	Both
Coastal Management Act	Protects coastal resources & supports water-dependent uses	Regulates development that impacts coastal water & resources	Yes	Yes	State & Local	Both

The Connecticut Stormwater Quality Manual provides guidance on the measures necessary to protect the waters of the State of Connecticut from the adverse impacts of post-construction stormwater runoff. The stormwater management measures are designed to preserve pre-development hydrology; reduce average annual TSS loadings by 80% post-construction; preserve and protect natural drainage systems; manage runoff velocities and volumes; prevent pollutants from entering receiving waters; and, seek multi-objective benefits. The Stormwater Quality Manual focuses on site planning, source control and stormwater treatment practices, and is intended for use as a planning tool and design guidance document by the regulated and regulatory communities involved in stormwater quality management in Connecticut.

APPENDIX C

LOW IMPACT DEVELOPMENT RESOURCES

U.S. Environmental Protection Agency Low Impact Development:
http://www.epa.gov/owow/nps/lid/

Low Impact Development Center: http://www.lowimpactdevelopment.org/

Center for Watershed Protection, Stormwater Manager's Resource Center:
http://www.stormwatercenter.net/

University of New Hampshire Stormwater Center: http://www.unh.edu/erg/cstev/

National LID Clearinghouse: http://www.lid-stormwater.net/clearinghouse/index.html

Prince George's County, Maryland:
http://www.princegeorgescountymd.gov/Government/AgencyIndex/DER/ESG/Bioretention/pdf/Bioretention%20Manual_2009%20Version.pdf

Connecticut Nonpoint Education for Municipal Officials (CTNEMO):
http://nemo.uconn.edu/

Jordan Cove Urban Watershed Project:
http://www.jordancove.uconn.edu/jordan_cove/about.html

North Carolina State University/North Carolina Cooperative Extension Stormwater Engineering Group: http://www.bae.ncsu.edu/stormwater/

Puget Sound Partnership Resource Center:
http://www.psparchives.com/our_work/stormwater/lid.htm

Villanova Urban Stormwater Partnership: http://www3.villanova.edu/vusp/

Street Edge Alternatives (SEA Streets) Project:
http://www.seattle.gov/UTIL/About_SPU/Drainage_&_Sewer_System/GreenStormwaterInfrastructure/NaturalDrainageProjects/StreetEdgeAlternatives/index.htm

APPENDIX D

STORMWATER BMP MONITORING RESOURCES

International Stormwater BMP Database: http://www.bmpdatabase.org/

Urban Stormwater BMP Performance Monitoring Manual:
http://water.epa.gov/scitech/wastetech/guide/stormwater/upload/2009-Stormwater-BMP-Monitoring-Manual.pdf

U.S. Environmental Protection Agency Urban Stormwater Performance Monitoring:
http://water.epa.gov/scitech/wastetech/guide/stormwater/monitor.cfm

U.S. Environmental Protection Agency National Menu of Stormwater BMPs:
http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm

U.S. Department of Transportation Federal Highway Administration Storm Water Management: http://www.environment.fhwa.dot.gov/ecosystems/wet_storm.asp

National Stormwater Quality Database:
http://rpitt.eng.ua.edu/Research/ms4/Paper/Mainms4paper.html

Center for Watershed Protection Monitoring to Demonstrate Environmental Results: Guidance to Develop Local Stormwater Monitoring Studies:
http://basineducation.uwex.edu/centralwis/pdfs/StormwaterMonitoringGuidance.pdf

Center for Watershed Protection, Stormwater Manager's Resource Center, Monitoring and Assessment: http://www.stormwatercenter.net/

Water Environment Research Foundation:
http://www.werf.org/AM/Template.cfm?Section=Stormwater3

New England Interstate Water Pollution Control Commission:
http://www.neiwpcc.org/

University of New Hampshire Stormwater Center: http://www.unh.edu/erg/cstev/

Portland Bureau of Environmental Services Sustainable Stormwater Monitoring Performance: http://www.portlandonline.com/bes/index.cfm?c=36055

Municipal Research & Services Center of Washington BMPs for Storm and Surface Water Management: http://www.mrsc.org/Subjects/Environment/water/SW-BMP.aspx

GLOSSARY

Adsorption: The adhesion of a substance to the surface of a solid or liquid (USEPA, 2002; Prince George's County, 2007).

Automated Sampler: A programmable mechanical and electrical instrument capable of drawing a single grab sample, a series of grab samples or a composite sample (GC&WWE, 2009).

Biofiltration: The simultaneous process of filtration, infiltration, absorption and biological uptake of pollutants in stormwater that takes place when runoff flows over and through vegetated areas (USEPA, 2002).

Bioretention: A concept that originated in the early 1990s by the Prince George's County, MD, Department of Environmental Resources. A stormwater practice that uses shallow storage, landscaping and soils to control the quality and quantity of water by collecting it before it's filtered through plantings and soil media (Prince George's County, 1999; USEPA, 1999b; 2002; Dunnett and Clayton, 2007).

Combined Sewer Overflow (CSO): A discharge of untreated wastewater from a combined sewer system at a point to the headworks of a publicly-owned treatment facility. CSOs generally occur during rainfall events or snowmelt when these systems become overloaded, bypass treatment plants and discharge directly to receiving waters (USEPA, 2002; 2004b).

Combined Sewer System (CSS): A wastewater collection system that conveys sanitary wastewaters (domestic, commercial and industrial) and stormwater through a single pipe to a publicly-owned treatment facility for treatment prior to discharge to surface waters (USEPA, 2002; 2004b).

Composite Sample: Sample composed of two of more discrete samples. The aggregate sample reflects the average water quality covering the compositing or sample period (USEPA, 2002).

Concrete Frost: Saturated soil under freezing soil temperatures acts as a barrier with little infiltration capacity (Brooks et al., 2003; LeFevre et al., 2009).

Event Mean Concentration (EMC): A statistical parameter used to represent the flow-weighted average concentration of a given parameter during a storm event and is defined as the total constituent mass divided by the total runoff volume (GC&WWE, 2009).

Grab Sample: An individual sample collected within a short period of time at a particular location (GC&WWE, 2009).

Granular Frost: Unsaturated porous soil under freezing soil conditions allow for more infiltration capacity (Brooks et al., 2003; LeFevre et al., 2009).

Impervious Surface/Cover: A hard surface area, such as building rooftops, walkways, patios, driveways, parking lots/storage areas, concrete/asphalt paving, gravel roads, packed earthen materials and oiled surfaces, which either prevents or retards the entry of water into the soil, as well as soil moisture from evapotranspiring to the atmosphere. (USEPA, 2002; Chabaeva et al., 2009).

Low Impact Development (LID): A concept that was pioneered by Prince George's County, MD, Department of Environmental Resources in the early 1990s. An innovative approach to urban stormwater management with the primary goal of maintaining or mimicking a site's predevelopment hydrology using design techniques that infiltrate, filter, store, evaporate, and detain runoff close to its source (Prince George's County, 1999; USEPA, 2000b; Dietz, 2007).

Municipal Separate Storm Sewer System (MS4): A conveyance or system of conveyances owned by a state, city, town or other public body, that is designed or used for collecting or conveying stormwater, which is not a combined sewer, and which is not part of a public-owned treatment facility (USEPA, 2002; 2010).

National Pollutant Discharge Elimination Systems (NPDES): The national program for issuing, modifying, revoking and reissuing, terminating, monitoring and enforcing permits, and imposing and enforcing pretreatment requirements under Sections 307, 318, 402 and 405 of the Clean Water Act (USEPA, 2002; 2004b).

Nonpoint Source (NPS) Pollution: Pollution that enters a water body from diffuse origins on the watershed and does not result from discernible, confined or discrete conveyances. It occurs when rainfall or snowmelt moving over and through the ground, picks up and carries away pollutants that are deposited into rivers, lakes and coastal waters, or introduces them into the ground water (USEPA, 1996; 2002).

Non-Structural Best Management Practices (BMPs): Institutional and pollution-prevention practices designed to prevent or minimize stormwater pollution and/or reduce the volume of stormwater requiring management using natural measures (USEPA, 1999a; 2002).

Point Source: Any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fixture, container, rolling stock, concentrated animal feeding operation, landfill leachate collection system, vessel or other floating craft from which pollutants are or may be discharged (USEPA, 2002; 2004b).

Rain Garden: Synonymous with bioretention, the term is typically used for marketing and general audience discussions (PGC, 2007).

Snowpack: mixture of ice crystals, air, impurities and liquid water, if melting (Brooks et al., 2003).

Stormwater Best Management Practices (BMPs): Methods, measures or practices selected by an agency to meet its nonpoint source control needs, i.e., water quality goals. BMPs include structural and non-structural controls, and operation and maintenance procedures that can be applied before, during and after pollution-producing activities to reduce or eliminate the introduction of pollutants into receiving waters (40CFR130.2, 1976).

Stormwater Control Measure (SCM): Physical, structural and /or managerial measures that, when used singly or in combination, reduce the downstream quality and quantity impacts of stormwater (NRCNA, 2009).

Structural Best Management Practices (BMPs): Engineered and constructed systems that are used to treat stormwater at either the point of generation or the point of discharge to either the storm sewer system or to receiving waters (USEPA, 1999a; 2002).

Total Maximum Daily Load (TMDL): The amount of pollutant, or property of a pollutant, from point, nonpoint and natural background sources, that may be discharged to a water quality-limited receiving water. Any pollutant loading above the TMDL results in violation of applicable water quality standards (USEPA, 2002; 2004b).

Total Suspended Solids (TSS): A measure of filterable solids present in a sample, as determined by the method specified in 40CFR136 – Guidelines Establishing Test Procedures for the Analysis of Pollutants (USEPA, 2002; 2004b)

Underdrain: A perforated pipe that is placed longitudinally at the invert of a bioretention facility for the purposes of achieving a desired discharge rate (PGC, 2007).

Water Quality Standards (WQS): A law or regulation that consists of the beneficial use or uses of a waterbody, the numeric and narrative water quality criteria that are necessary to protect the use or uses of that particular waterbody, and an antidegradation statement (USEPA, 2002; 2004b).

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